Energy-efficient cooking
The EffiCooker

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Energy Efficient Cooking

The EffiCooker

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Abstract

The purpose of this work is to investigate the energy losses in electric surface cooking and how to minimize them. The case of cooking with *dry heat* (frying) is only treated superficially, concentrating on cooking with *moist heat* (boiling, steaming).

The theoretical losses are calculated for a conventional pan used with a conventional glass-ceramic range and for two types of electric pan, one thermally insulated and the other without insulation. The calculated losses compare fairly well with the actual, measured losses.

It is concluded that in order to minimize energy consumption the following three measures should be taken: (1) Integrate heating element in pan, (2) Isolate pan, (3) Provide an "intelligent" power control. A working prototype of a saucepan, dubbed the EffiCooker, is constructed according to these principles.

To demonstrate the energy saving some common cooking tasks are performed with the EffiCooker as well as with ordinary equipment. In these examples energy savings range from 28% to 81%.

Furthermore, the EffiCooker is very user friendly. Many cooking tasks, once initiated, are performed automatically without any further user attention. The EffiCooker also may replace many other kitchen appliances.

Further development might involve improved thermal insulation, reduced heat capacity, pressure cooking, improved controller, and a more attractive appearance.

Keywords: Energy Efficient Cooking, Energy Conservation, Saving Energy

Dansk Resumé

Formålet med dette arbejde er at undersøge årsagerne til energispild ved madlavning på elektriske komfuroverplader, og hvordan spildet kan reduceres. Arbejdet koncentrerer sig om kogning og dampning; stegning berøres kun periferisk.

De teoretiske energitab beregnes for en almindelig gryde på et almindeligt glas-keramisk komfur og for to typer elgryde, den ene termisk isoleret, den anden uisoleret.

Konklusionen er, at disse tre forholdsregler bør tages: 1) Varmelegemet skal indbygges i gryden, 2) Gryden skal isoleres, 3) Den skal forsynes med en "intelligent" styring. I henhold til disse principper er der konstrueret en prototype, kaldet EffiCooker.

For at vise hvor meget energi der kan spares, er der udført nogle almindelige former for madlavning, dels med EffiCooker, dels med almindeligt køkkenudstyr. I disse eksempler varierer besparelsen fra 28% til 81%.

EffiCooker er desuden meget brugervenlig. Mange madlavningsprocesser kan forløbe automatisk uden indblanding fra brugeren, når de én gang er startet. EffiCooker kan også erstatte mange andre køkkenapparater.

Af eventuelle mulige forbedringer kan nævnes: bedre termisk isolering, nedsat varmekapacitet, trykkogerfunktion, forbedret styring og et mere tiltrækkende design.

Contents

Preface

This work is inspired by work done previously at Physics Laboratory III, Technical University of Denmark: Electronically Controlled Kitchen Range [2], Development and Testing of Electric Saucepan With Power Control [3], Towards a Lower Electricity Consumption [4]. In the present work the energy consumptions of three different types of saucepan are evaluated. Based on this a saucepan with integrated heating element and thermal insulation is combined with an effective electronic control to form a very energy-efficient and user friendly cooking appliance: the EffiCooker.

1 Heating Food

Food is heated for many reasons. Some of them are

- To improve taste, nutritive value, and digestibility
- To release disagreeable odors and flavors
- To seal up natural juices or the reverse
- To destroy toxins and unwanted microorganisms
- To reduce

The object is to obtain a cooked food with a pleasing appearance, taste, and texture. Economy and retained nutritional value are expected. Some foods just need to be heated to a certain temperature, like tender cuts of meat. Others must be kept at an elevated temperature for a certain time, like vegetables or tough meat cuts [5][6][8].

1.1 Moist or dry heat

"On devient cuisinier mais on naît rôtisseur" (literally, "One becomes a cook but one is born a roaster") said famous culinary writer Jean Anthelme Brillat-Savarin (1755...1826) [13].

1.1.1 Moist heat

When food is heated in a container in the presence of ample water, and ample heat is applied, then the temperature will stabilize at the boiling point of water (100°C). The temperature cannot rise above the boiling point because the surplus energy will be expended evaporating water. This so-called *moist heat* cooking is an easy way of achieving a constant, well-defined temperature; it has probably been used ever since our ancestors learned how to make suitable cooking vessels. In this work we concentrate on this kind of cooking heat.

Boiling is cooking food immersed in boiling liquid, usually water. Heat is transferred to the food through convection in water. In *steaming* the food is not covered by water; instead heat is transferred from boiling water to food in a closed container by steam. As the temperature approaches the boiling point the space above the water is almost entirely filled with vapor, most of the air being expelled. The *steaming temperature* must be maintained slightly below the boiling point; thus a pressure difference exists that forces the steam from the surface of the boiling water to the food, where it condenses, giving off heat. This also ensures that little steam will escape, provided the lid is reasonably tight-fitting. It also means that the cooking time will be somewhat longer. In the EffiCooker, described later, the steaming temperature is fixed at 95°C, and the measured steam emission is approx. 7 g/h, corresponding to 4 W.

Steaming may be carried out in an ordinary covered pan, with just a minimal amount of water at the bottom. The food may be placed on a perforated steam plate or basket, or it may rest directly on the pan bottom. For types of food that do not "cling" to the pan bottom it is of no practical consequence whether the food is partly submerged or not. It follows that much less water is needed for steaming than for boiling; this may lead to substantial savings of time and energy, simply because less water has to be heated. Besides, less nutrients are leached from the food [6], and even so the cooking water ends up being more concentrated and better suited for sauce making.

In some cases steaming is not feasible, for example if the food – for some vague reason – must be cooked in salted water, or if it is supposed to absorb much water, like rice or pasta, or for the preparation of soup or stew. Otherwise steaming should be preferred to boiling.

When using an ordinary cooking surface the heat must be set manually. A high initial setting is necessary to accomplish fast boil-up, then the heat must be lowered to maintain just the right degree of boiling. Turning down the heat too late, or selecting a too high setting for continued boiling, will cause waste of energy through excessive evaporation; in the opposite case the food may not be done as expected. Even for a careful user it may prove difficult to administer the heat properly, i. e. getting the food done without undue waste of energy. Also one must monitor the process closely to determine when the correct cooking temperature has been reached, in order to achieve correct timing. In the EffiCooker these problems have been solved by the automatic control (see Electronic controller, p. 15).

It should be noted that the boiling point temperature stated for water, 100°C, is valid for pure water at normal atmospheric pressure only. The boiling point is affected by solutes or colloids in the water and by the pressure in the vessel.

Dissolved e. g. salt or sugar will elevate the boiling point. The boiling point elevation ΔT_b due to the presence of a solute or colloid is a so-called colligative property, which means that it is dependent on the number, not the kind, of dissolved particles. For ideal solutions of non-volatile solutes in low concentrations it may be expressed as

$$\Delta T_b = K_b \cdot m \cdot i$$

K_b boiling point constant of solvent. For water K_b = 0.51°C/(mole/kg)

m molality of solution (moles of solute/kg of solvent)

i van ´t Hoff factor; number of individual particles per molecule of compound in solution

E. g. for sucrose (table sugar) $i = 1$, for sodium chloride (table salt) $i = 2$, because sucrose is not dissociated, whereas a salt molecule is dissociated into two ions: Na^+ and Cl^-. The molecular masses are $M_{sugar} \cong 342$ and $M_{salt} \cong 58$.

The boiling point elevation for a 1% salt solution (or 10 g salt/kg water, the concentration often used to boil e. g. pasta or vegetables) will be

$$\Delta T_b = K_b \cdot m \cdot i = K_b \cdot \frac{10}{M} \cdot i \cong 0.51 \cdot \frac{10}{58} \cdot 2 \cong 0.18\,°\mathrm{C}$$

For a 10% sugar solution (111 g sugar per kg water) it will be

$$\Delta T_b = K_b \cdot m \cdot i = K_b \cdot \frac{111}{M} \cdot i \cong 0.51 \cdot \frac{111}{342} \cdot 1 \cong 0.17\,°\mathrm{C}$$

1% salt or 10% sugar in solution both cause about the same, negligible, boiling point elevation of just under 0.2°C. Obviously the boiling point elevation must be taken into account only at rather high concentrations of salt or sugar [17].

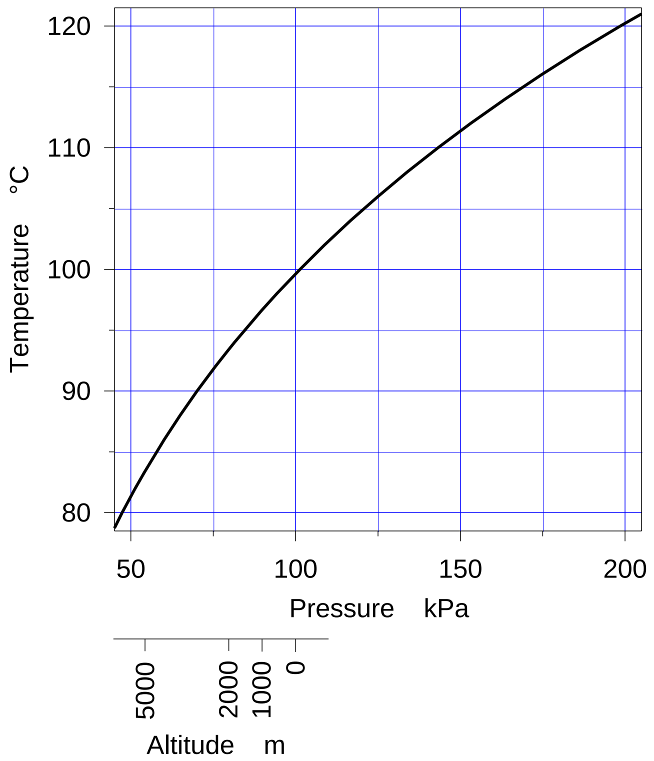

Figure 1. Boiling point of water as a function of pressure and altitude

Figure 1 shows the boiling point at various pressures and altitudes. Changes in weather conditions, apart from extreme situations like hurricanes, may cause the barometric pressure at sea level to deviate from normal by –7 to +5 kPa [1]. The corresponding boiling point range is about 98 to 101.5°C. Boiling point variations this small have only minor impact on cooking; e. g. the cooking time for a soft boiled egg increases by approx. 20 seconds when the cooking temperature is lowered by 2°C (see Soft-cooked eggs, p. 26). When designing devices for the automatic control of boiling or steaming even small changes in boiling point temperature must be taken into account (see p. 16).

The reduced pressure experienced at higher altitudes may have a more pronounced effect. E. g. at 2000 m the pressure and boiling point are approx. 80 kPa and 93°C, respectively, a boiling point depression of about 7°C, large enough to have an appreciable effect on cooking.

Pressure cookers are often operated at approx. 200 kPa, about twice the normal atmospheric pressure, corresponding to approx. 120°C. Using a pressure cooker may eliminate the effects of varying atmospheric pressure, as the internal pressure may be controlled independently.

1.1.2 Dry heat

In the absence of free, liquid water (cooking with *dry heat*) the temperature may rise above that of the boiling point. At such temperatures browning of the food is possible. Browning usually confers desirable colors and flavors to the food. It is due mainly to two nonenzymatic, chemical reactions: *Caramelization* and the *Maillard reaction*. Caramelization occurs when a sugar is heated to a certain temperature, possibly over its melting point, causing it to form various polymerized, brown colored compounds. Different types of sugar caramelize at temperatures from 110 to 180°C. For the Maillard reaction to take place at a reasonable speed the temperature must exceed approx. 140°C; sugars and amino acids react to form a wide variety of brown colored, palatable compounds. However, at too high temperatures the food may scorch, and there is also the risk that carcinogenic compounds may be formed [6][8]. Examples of dry heat cooking methods (their major principles of heat transfer given in parentheses) are *frying* (conduction), *deep fat frying* (convection), *roasting* (radiation), and *barbecuing* (convection and radiation). The cook must be able to select the method and temperature that will bring about the desired browning but no scorching. According to M. Savarin one must be born with that faculty.

2 Saving Energy in Electric Cooking

Much of the heat expended in cooking does not end up where it is wanted: in the food. In barbecuing, for example, as little as 1% of the expended energy may actually end up in the food. This is the case if you use equal amounts by weight of meat and charcoal.

Heat lost during (indoor) cooking is not always completely lost; in the heating season it may be put to good use heating the house, although it probably represents a higher quality form of energy than does that used for space heating. Otherwise, in the cooling season it incurs an extra load on the air-conditioning system.

The following applies to moist heat cooking on an ordinary electric cooking surface with resistance heating in particular.

There are several ways through which energy is consumed. Heat is stored in the heat capacities (thermal masses) of hotplate, pan, and water, and eventually lost to the surroundings; we call it *fixed energy loss*, as it is independent of the duration of the cooking task. The heat stored in the heat capacity of the food also belongs in this category, except that it is not considered lost, of course. The heat rejected to the surroundings by conduction, convection, and radiation, and lost evaporating water, is called *running energy loss*. It is dependent on the duration of the process. The total energy consumed in a process is the sum of the fixed and the running energies.

The following items will be investigated below to minimize energy waste: *Hotplate, Pan, Water, Control and Timing, Pressure Cooking, Heat Pump, User-friendliness, and Recipe.* They represent measures that may be taken by the equipment manufacturer as well as by the user.

Heating by induction or microwaves eliminates some of the heat losses mentioned above, but incurs an additional loss inherent in the conversion of electricity to high frequency. The resulting energy efficiency may be comparable to that of conventional methods. It will probably improve with future technological advancements.

2.1 Hotplate

Figure 2 is a simplified section view of a conventional pan sitting on a glass-ceramic cooking surface. Beneath the panel is the heating unit, in this case of the Ceramaspeed™ [12] make. The glass-ceramic material is glass that has been heat treated to partly turn it into ceramic. Through this treatment its coefficient of expansion is brought close to zero, making it able to withstand sudden temperature changes. The low thermal conductivity makes for relatively low energy losses through horizontal conduction through the panel. The material also features a fairly good infrared transmission. These properties are the reason for the extensive use of glass ceramics for smooth cooking surfaces.

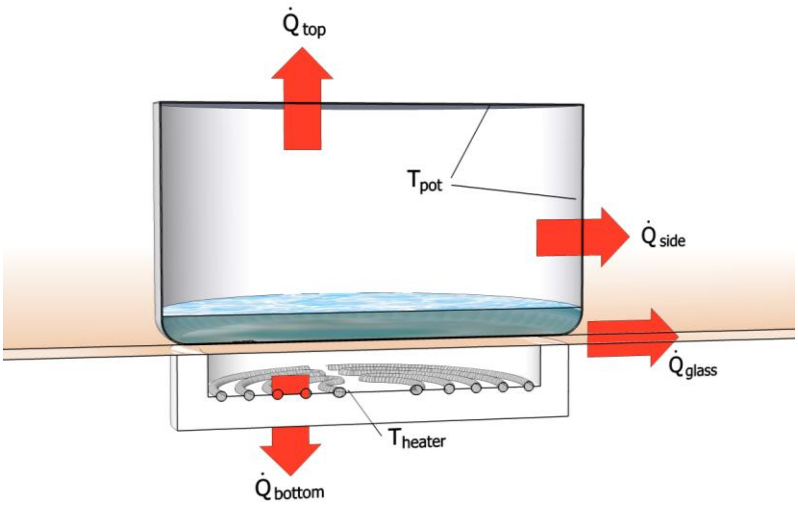

Figure 2. Heat losses from conventional pan on range

German manufacturer Schott is one supplier of glass-ceramic panels. Their product Ceran Suprema® [10] has a specific thermal conductivity $k = 1.7$ W/(m·K), similar to that of ordinary glass, and of course much less than e. g. stainless steel (about 14 W/(m·K)). The 4-mm panel's horizontal thermal conductivity corresponds to that of a stainless steel sheet of 0.5 mm thickness.

The heating unit comprises a bowl-shaped heater carrier made of insulating material. The heating element is a helically wound resistance filament fitted in a groove in the carrier. The element must not come into contact with the glass panel for safety reasons, as the electric insulation properties of the panel are inadequate at high temperatures. Heat transfer from the heating element to the pan is through radiation, convection, and conduction. A temperature limiter switch (not shown in the figure) is placed so as to sense the temperature in the space above the heating filament. The limiter prevents the temperature rising above a safe level, usually 500...600°C.

The Ceramaspeed™ heating unit is based on a so-called microporous insulating material called Microtherm®. With 90% void space and pore dimensions less than the mean free path of air molecules it attains a thermal conductivity of $k = 0.022$ W/(m·K) (at 100°C), actually less than that of still air ($k = 0.038$ W/(m·K)) [12].

Four principal heat flows are shown: $\dot{Q}_{top}$, $\dot{Q}_{side}$, $\dot{Q}_{glass}$, and $\dot{Q}_{bottom}$, that make up the total heat loss from the heater-cooktop-pan combination. Of these $\dot{Q}_{glass}$ and $\dot{Q}_{bottom}$ are attributed to the hotplate. Besides, heat is stored in the heat capacities of heater and part of the glass-ceramic panel. The following measures to minimize heat loss from the hotplate may be considered:

- Use flat-bottomed pan that fits the size of the heating area. The pan should be slightly larger in diameter than the heating zone so as not to leave any part of the zone exposed.
- Insulate hotplate. Most of the heat loss is through conduction horizontally through the glass-ceramic panel. Employing a material with a lower ratio of specific heat conductance to mechanical strength would reduce it, but this probably cannot be done at the present state of the art.
- Minimize thermal mass of hotplate. Most of the thermal mass is in the glass-ceramic panel. Reducing it would require a material with less specific heat in proportion to mechanical strength, which is probably not feasible at present.
- Completely eliminate hotplate, i. e., integrate heating element in pan. Besides reducing losses this approach also results in faster response when turning the heat up and down, which in itself may lead to less energy waste.

2.2 Pan

Energy is lost heating the thermal mass of the pan and transferring heat from pan to surroundings. To minimize these losses

- Cover pan. Not always feasible, e. g. when frying, or if stirring is required, or if recipe calls for uncovered pan.
- Minimize thermal mass of pan. There is probably not much to be done in this respect.
- Insulate pan. There are dual-wall pans on the market [14]. Using them would surely bring about a certain energy saving.

2.3 Water

Energy is lost heating and evaporating water. To minimize these losses

- Use steaming rather than boiling, whenever possible, to minimize the amount of water.
- Control the heat so as to not let water boil excessively, yet still supply sufficient heat to cook food. As an added benefit less water vapor is given off to the surroundings, where it would otherwise increase the humidity of the indoor atmosphere.

2.4 Control and timing

As mentioned above, tight control of the supplied heat helps avoid energy loss. Such control is difficult to provide automatically unless there is a means of temperature measurement in the pan itself. It has not been done with any success, as far as is known, through sensors integrated in the cooking surface. Electric skillets and pans on the market are usually equipped with some form of thermostat. Even though such a thermostat is based on a sensor inside the pan, it does not work well controlling boiling or steaming. You either get excessive boiling or no boiling, or a steady alternation between the two.

Timing is equally important. If an automatic timer is used – and set correctly – the heat is turned off at such time that the cooking process may just finish "using up" the available heat. Also the heat will be turned off even if the user is inattentive.

2.5 Pressure cooking

Pressure cooking may save energy due to the shorter cooking time. It may be the only means of boiling or steaming food at higher elevations.

2.6 Heat pump

Employing a heat pump in ordinary cooking is not considered practicable at the present state of the art. Still, the prospects are bright: the COP (**C**oefficient **O**f **P**erformance, efficiency) of an ideal, reversible heat pump operating between reservoir temperatures of T_l = 20°C and T_h = 100°C is

$$COP_{HP} = \frac{T_h}{T_h - T_l} \cong \frac{100+273}{100-20} \cong 4.7$$

where T_h and T_l are inserted in kelvin. The practical efficiency is lower, but may still be well over 1. If a COP of 2 could be achieved it would mean halving the cooking energy consumption, as compared to resistance heating, everything else being equal.

2.7 User-friendliness

Most cooks are probably more concerned with their culinary achievements than with the conservation of energy. Therefore it is a good idea that the equipment induce the user to more or less instinctively save energy. E.g. the automatic control of the EffiCooker may tempt the user to steam food rather than boil it in order to save time, involuntarily saving energy as well.

2.8 Recipe

Select an energy efficient recipe. What was stated above about cooks probably also is true of many cookbook authors: they don't pay much attention to energy conservation. For example, a recipe requires a single dish to be prepared on several surface units then finally in the oven; if it could all be done in the oven it would save energy. Or a recipe calls for an excessive amount of water (see Boiling pasta, p. 31).

3 EffiCooker: The Electric Pan

An electric pan, dubbed the "**EffiCooker**" (**Effi**cient **Cooker**), has been constructed according to the above. It features thermal insulation, integrated heating element, and an "intelligent" controller and timer which, among other things, provides for easy and energy efficient steaming.

3.1 Construction

The functional prototype is made out of two ordinary stainless steel pans, the smaller one fitted inside the larger one, so as to form a double-wall vessel. The two are bonded together along the rim using a silicone sealant. Figure 3 shows an x-ray, and Figure 4, a section view. Unfortunately, the bead of silicone sealant forms a rather substantial thermal bridge and thermal capacity, as is evident from the section view. The "double-glazing" lid consists of two ordinary transparent lids glued together along the edge, using the same silicone adhesive as is used for the pan.

Figure 3. X-ray view of EffiCooker

The heating element is a 1400 W resistance filament encapsulated in a meander-shaped stainless steel tube. It is brazed onto the outside of the bottom of the inner pan and so conveniently concealed within the air space between the two pans. It would have been a good idea to sandwich a heat-distributing plate of e. g. copper or aluminum between the pan bottom and the heating element, but this has been left out in the present prototype. In mass production other types of heating element, e. g. a foil type, might be considered, that afford a more even heat distribution.

Figure 4. Section view of EffiCooker

The dual-wall construction is used in order to reduce running thermal losses. We shall show later that losses are reduced by a good 50% (Table 8, p. 24). Besides, it makes for easier handling, because the outer surfaces are kept cool to the touch. For example, you need no kitchen mitts to drain the water from the vegetables, if you are not too thin-skinned. The insulation properties might have been further improved by vacuum or some sort of insulation in the gap.

The protruding ends of the heating element form an electrical power connector on one side of the pan. Adjacent to it is a connector for carrying the temperature measurement signals (not shown in the drawing). It is important that the user keep the connector clean and dry when in use in order to avoid short circuits.

The sealant used is Dow Corning 3145, an RTV (**R**oom **T**emperature **V**ulcanizing) silicone rubber, claimed to be heat resistant to 200°C continuous [11]. It is used because it withstands heat and readily adheres to metal and glass. Unfortunately, the water vapor permeability of silicone rubber is high, which means that moisture may penetrate into the closed space between the inner and outer walls in pan or lid. In a mass production of course some other bonding method, like welding, must be employed, so as to make the pan dishwasher-safe.

A separate base unit is designed to accommodate the cooker when in use. The unit contains electronic controller, display, and control knobs. When the cooker is placed in operating position on the base (Figure 5, center), its connector makes contact with a matching connector on the base. In the figure the two controls are visible in front, and behind the cooker is the rear panel with display.

Figure 5. EffiCooker flanked by rice cooker (left) and ordinary pan

3.2 Electronic controller

The electronic controller resides inside the base. It consists of a PCB (**P**rinted **C**ircuit **B**oard) with a microprocessor and various input/output circuits, an LCD (**L**iquid **C**rystal **D**isplay), and two control knobs, both serving as rotating dials and as pushbuttons.

The controller determines the amount of electric power to be supplied to the heating element, based on the user's wishes, and the temperature inside the pan. It also works as a timer to end the cooking process once the predetermined cooking time is up.

The left control knob facilitates selection of *boiling*, *steaming*, or a certain *temperature*. When *boiling* is selected the controller aims at a gentle boil, maintaining the temperature of the food at the boiling point. When *steaming* the controller attempts to maintain the temperature of the vapor above the water surface at 95°C. This fixed *steaming temperature* must be somewhat less than the boiling point (see Moist heat, p. 7). In both *Boil* and *Steam* there are 9 settings, numbered 1...9 that control the maximum power of the heating element during warm-up. E. g. to scald milk a low setting, like Boil 3 should be selected in order to avoid scorching but still end up at the boiling point. *Temperature* settings are used when not boiling or steaming. E. g. to slow-cook a stew one might select a temperature of 80°C in connection with a time of several hours. For deep fat frying a temperature of 180°C might be selected. Pushing the left button turns the power on or off.

Whether you select boiling, steaming, or temperature, the controller provides tight regulation of the power delivered to the heating element, keeping energy consumption to a minimum. High power is applied as necessary at the beginning to accomplish fast boil-up. Boiling over is prevented, and in case of boiling dry the power is shut off.

The scheme for boiling and steaming is designed for a boiling point in the range of 98°C...102°C, i. e. cooking at sea level with only modest concentrations of solute in the water (see p. 8). In its present form it will not work at reduced pressure (high altitudes) or increased pressure (pressure cooker). For such applications modifications of the controller will be necessary.

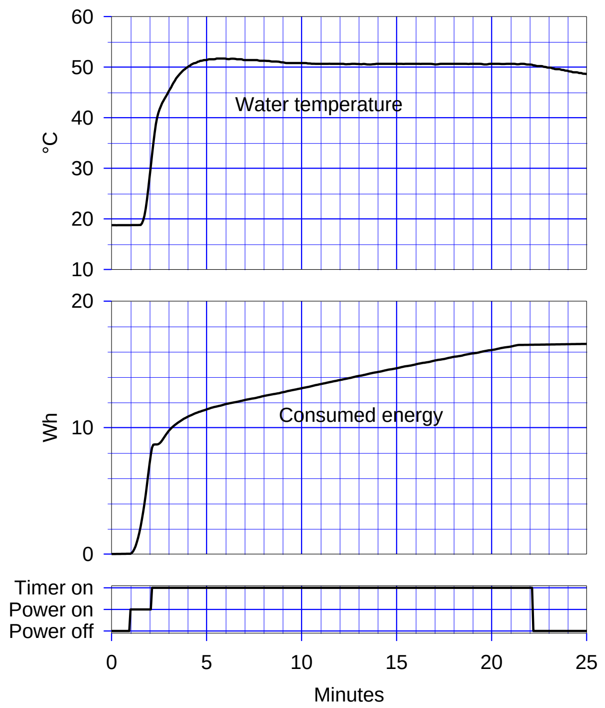

Figure 6. Heating and keeping 200 g water at 50°C for 20 minutes

The control to the right is the *timer* setting. It may be set anywhere between 2 seconds and 4 hours. The selected cooking time, shown on the display, may be adjusted whenever you want, even during countdown. The timing starts automatically once the required condition (steaming, boiling, or the selected temperature) is satisfied, so it metes out the actual cooking time accurately. The timer may also be started or stopped manually by pushing the button. The selected time as well as the elapsed and the remaining time are shown on the display. When the time expires an acoustic signal is emitted, and shortly before that the power is turned off. Usually no user attention is required once the process is started.

Figure 6 shows an example of heating water to a set temperature of 50°C. The water temperature "overshoots" to 52°C then stays at about 51°C. Steaming is illustrated in Figure 9, p. 29, and Figure 10, p. 33; the vapor temperature is seen to remain close to 95°C. The graphs also display the timer operations and consumed energies.

In its present form the controller performs fairly well in most cases. In a future project it might be further refined, particularly to improve reliability when preparing very small or very large amounts of food.

3.3 User convenience

Due to its good thermal properties and "intelligent" control the EffiCooker doubles as a

- Steamer
- Rice cooker
- Double boiler
- Deep fat fryer
- Egg cooker
- Chocolate melter
- Slow cooker ("Crock-pot")
- Pressure cooker (requires further development)

Many cooking tasks may be carried out automatically. Once started, no further user intervention is required. Tasks that are easily carried out, in addition to common cooking, include

- Scalding milk
- Reducing
- Thawing frozen food
- Reheating food
- Keeping food warm

The thermal insulation provides for easy handling: No oven mittens are required to drain the water from the vegetables. If one can tolerate a pan on the dining table it may be used for serving; the food will stay warm longer.

3.4 Cost

The EffiCooker will of course be somewhat more expensive than the simpler appliances that are on the market. It is difficult to come up with an exact price; it depends very much on the production batch size. Because it replaces many appliances, and because of its energy efficiency and user friendliness, the higher price is considered to be justified.

4 Energy Consumptions

The theoretical energy losses are calculated for a conventional pan used with a conventional glass-ceramic range, for a simple, uninsulated electric pan, and for the EffiCooker, all three being similar in volume. Calculations include the running losses: the steady-state convection and radiation losses, as well as the fixed losses: the energies needed to heat the heat capacities (thermal masses) of pans and hotplate. We consider the case of steaming (hence the shallow layer of water). The convection heat losses for top, side, and bottom are calculated separately and independently, ignoring the fact that the convection currents probably will reinforce each other. Also the thermal bridges, which are present in the EffiCooker, particularly along the edges of pan and cover, are ignored in the calculations. Therefore the actual losses may somewhat exceed the calculated ones.

The actual running losses are measured for the conventional pan and for the EffiCooker. The calculated losses turn out to compare fairly well with the measured losses, despite the reservations above (see Energy consumptions compared, p. 24).

The theoretical energy consumption when performing an actual cooking task may be calculated by summing the fixed energy and the running energy times the total time. This procedure does not treat the transient conditions correctly, nor does it take possible heats of reaction into account, still it results in a reasonable approximation to the measured energies. In the two cases (Table 14, p. 31, Table 17, p. 34) the difference is approx. 8%.

Table 1 shows the main features of the three pans. The dimensions are approximations, treating the pans as having plane and cylindrical surfaces. Details like handles, etc., are disregarded. The volume given is the useful volume, leaving about 20 mm free space at the top. All three pans are covered with transparent (glass) lids.

Table 1. Materials and dimensions of three types of pan

		EffiCooker inner pan	**EffiCooker outer pan**	**Simple electric pan**	**Ordinary pan**	
Pan	**Diameter**	175	200	175	175	mm
	Height	95	115	95	98	mm
	Height incl. lid		135	110	110	mm
	Volume	1.7		1.7	1.7	L
	Material	Stainless steel	Stainless steel	Stainless steel	Stainless steel	
	Mass	410		410	690	g
Sealing bead	**Material**	Silicone rubber				
	Mass	130				g
(Inner) lid	**Material**	Glass		Glass	Glass	
	Mass	400		400	405	g
Heater	**Material**	Stainless steel				
	Mass	125				g

In Table 2 some materials are listed along with physical properties. The values are taken from [7][10][11][12]. In some cases, when a property varies with temperature, or in case of discrepancies between sources or lack of knowledge of the exact compositions of materials, an approximate value is given.

The emissivity of stainless steel is quite dependent on the surface brightness, i. e. to what degree it is polished or oxidized. The chosen value of 0.3 is a "medium" value.

Experimental conditions and accuracies are estimated as follows, unless otherwise noted:

Temperatures: ± 0.5°C

Mass: ± 2 g ± 2%

Electric energy: class 2 meter or better

Room temperature: 20°C ± 2°C

Water temperature: 15°C ± 2°C

Table 2. Material properties

	Specific mass ρ **kg/m^3**	**Specific heat** c_p **J/(kg·K)**	**Thermal conductivity** k **W/(m·K)**	**Emissivity** ε
Stainless steel	8000	470	14	0.3
Constantan	8920	384	23	
Glass		800		0.8
Ceran	2500	800	1.7	
Microtherm			0.022	
Silicone rubber		1700		
Water	1000	4200		
Potatoes		3450		
Eggs		3320		
Beef		3080		

4.1 EffiCooker

Figure 7 is a simplified section view of the EffiCooker. Three principal heat flows are shown: $\dot{Q}_{top}$, $\dot{Q}_{side}$, and $\dot{Q}_{bottom}$, that make up the total running convection and radiation heat loss from the pan.

The calculations are presented in the appendix (EffiCooker heat loss, p. 42). Table 3 shows the results.

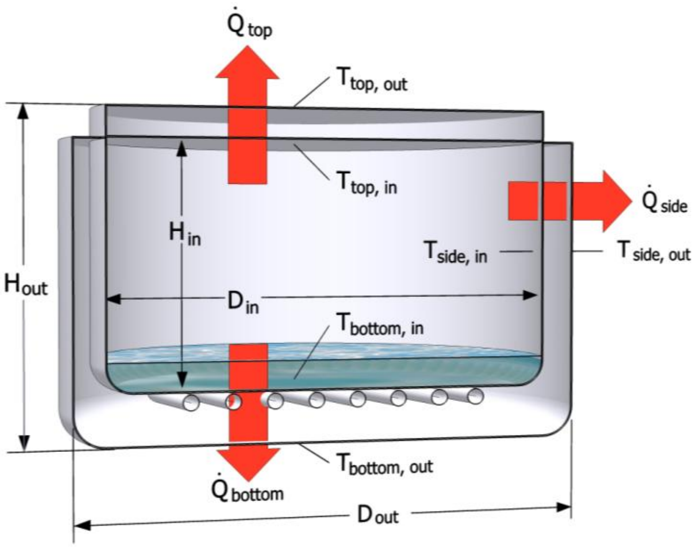

Figure 7. Heat losses from EffiCooker

Table 3. Theoretical energy losses of EffiCooker

Running energy losses				
Top	**Side**	**Bottom**	**Total**	
13	17.2	6	**36**	**W**

Fixed energy losses				
Inner lid	**Inner pan**	**Heater**	**Total**	
6.7	8.6	1.3	**17**	**Wh**

4.2 Simple electric pan

The simple, single-wall electric pan is treated in a similar way. It is shown in section in Figure 8 along with $\dot{Q}_{top}$, $\dot{Q}_{side}$, and $\dot{Q}_{bottom}$.

The heat losses are calculated in the appendix (Simple electric pan heat loss, p. 49) with the results shown in Table 4.

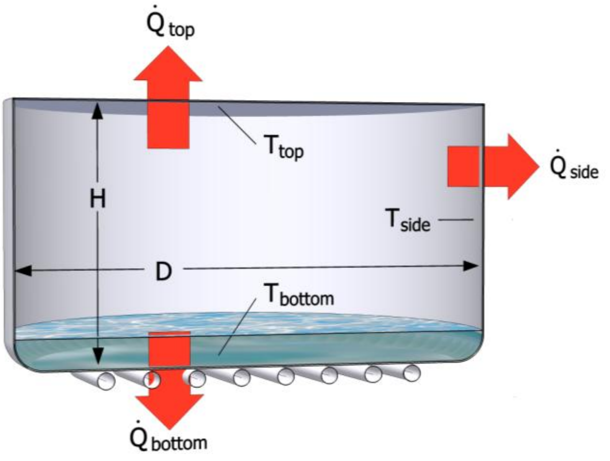

Figure 8. Heat losses from simple electric pan

Table 4. Theoretical energy losses of simple electric pan

Running energy losses				
Top	**Side**	**Bottom**	**Total**	
27.6	42.9	13.4	**84**	**W**

Fixed energy losses				
Lid	**Pan**	**Heater**	**Total**	
6.7	4	1.3	**12**	**Wh**

4.3 Conventional pan

See Hotplate, p. 11, for a description of the glass-ceramic panel and heating unit. Figure 2 is a simplified section view of a conventional pan sitting on a glass-ceramic cooking surface.

Four principal heat flows are shown: $\dot{Q}_{top}$, $\dot{Q}_{side}$, $\dot{Q}_{glass}$, and $\dot{Q}_{bottom}$, that make up the total running heat loss from the heater-cooktop-pan combination.

The calculations are presented in the appendix (Conventional pan heat loss, p. 52); Table 5 and Table 6 display the results.

Table 5. Theoretical running energy losses of conventional pan on range

Top	Side	Bottom	
27.6	42.9	7.6	**W**

Table 6. Theoretical fixed energy losses of conventional pan on range

Lid	Pan	Glass-ceramic panel	Heater	Total	
6.8	6.8	7.1	0.4	**21**	**Wh**

4.4 Measured energy losses

An experiment was conducted to measure the actual running heat losses from the ordinary pan on a glass-ceramic range and from the EffiCooker, when steaming at 95°C. A long time (several hours) was allowed for the temperatures to stabilize. The heat setting for the ordinary pan was selected so as to maintain the steaming temperature at approx. 95°C. The electricity consumptions and the evaporation rates were determined, and the heat losses taken to be the difference between the electricity consumption and the power spent in evaporating water. Table 7 shows the results.

The evaporation rate, determined by weighing, was in both cases approx. 7 g/h, corresponding to a power of

$$\dot{W} = \frac{m}{t} h_{fg} \cong \frac{0.007}{3600} 2257000 \cong 4\,\mathrm{W}$$

m mass of water [kg] evaporated in

t [s]

h_{fg} latent heat of vaporization of water [J/kg] $\cong$ 2257000 J/kg

Table 7. Measured running energy losses

	Ordinary pan on range	EffiCooker	
Electricity consumption	101	48	**W**
Evaporation	7	7	**g/h**
	4	4	**W**
Convection/radiation heat loss	**97**	**44**	**W**

4.5 Energy consumptions compared

In the following we compare the energy consumptions of three types of pan when steaming at 95°C. In Table 8 the calculated theoretical heat losses are presented, along with the total measured values for the EffiCooker and the ordinary pan. For the simple electric pan there are no measured values available. For the EffiCooker the actual running heat loss (44 W) exceeds the theoretical value (36 W) by 22%. It is assumed that the thermal bridges account for half of this (11%), and the reinforcement of convection currents for the other half (also 11%) (see Energy Consumptions, p.18). The corrected EffiCooker heat losses are set equal to the theoretical ones increased by 22%.

As the simple electric pan and the ordinary pan don't suffer from any thermal bridges, it is assumed that their relevant losses should be increased by 11% due to the convection currents only. This goes for the top and side losses of both, and the bottom loss of the electric pan. Finally, the energy loss of the ordinary pan through the glass-ceramic panel (11.2 W) is determined as the difference between the total measured loss (97 W) and the sum of the top, side, and bottom losses (85.8 W). In this way we arrive at the "Corrected" values in Table 8. Table 9 lists the theoretical fixed losses: the energies needed to heat the heat capacities of the three kinds of pan.

As the total heat losses of the EffiCooker and of the ordinary pan in Table 8 are measured directly, they may be considered fairly accurate. The other numbers in Table 8 and Table 9 must be regarded as estimates. Still, they are believed to give a useful idea of the loss distribution of the various types of pan. It appears that the tactics of providing dual walls and integrated heater are both justified. It also appears that the glass material of the lids incur a certain penalty, which is due to the relatively high specific heat capacity and emissivity of glass.

Table 8. Running energy losses of three types of saucepan

	Ordinary pan on range		**Simple electric pan**		**EffiCooker**	
	Theoretical W	**Corrected W**	**Theoretical W**	**Corrected W**	**Theoretical W**	**Corrected W**
Top	27.6	30.6	27.6	30.6	13	15.9
Side	42.9	47.6	42.9	47.6	17.2	21
Glass ceramic		11.2				
Bottom	7.6	7.6	13.4	14.9	6	7.3
Total		**97**	84	**93**	36	**44**

The energy consumption of a cooking task may be computed as the fixed energy plus the running energy loss times the total time of the task. As this calculation does not properly consider the transient conditions, and the possible heat of reaction is ignored, it represents an approximation only. Such a calculation has been done for the EffiCooker when steaming eggs (Table 14, p. 31) and potatoes (Table 17, p. 34). These calculations yield an impression of the various ways energy is lost in actual cooking tasks. For the tasks at hand the fixed energy losses dominate. For long-lasting tasks the reverse will be true.

Table 9. Theoretical fixed energy losses of three types of saucepan

	Ordinary pan on range **Wh**	**Simple electric pan** **Wh**	**EffiCooker** **Wh**
(Inner) lid	6.8	6.7	6.7
(Inner) pan	6.8	4	8.6
Glass ceramic	7.1		
Heater	0.4	1.3	1.3
Total	**21**	**12**	**17**

To further reduce the energy consumption of the EffiCooker one might try to minimize the thermal masses and improve the thermal insulation. Incidentally, about half (4.6 Wh) of the energy in the heat capacity of the EffiCooker inner pan would be eliminated in a production model, as it is due to the silicone rubber used to bond the inner and outer pan together (see Heat capacities, p. 48). One might also consider downsizing the Effi-Cooker, providing a more efficient appliance suited for small food quantities.

5 EffiCooker Versus Conventional Cooking

A number of actual cooking tasks are performed with the EffiCooker as well as with ordinary equipment. In most cases the energy consumptions are measured and compared.

5.1 Boiling water

The simple process of boiling water is often used as a means of describing the energy efficiency of cooking equipment, though it really doesn't tell much about the efficiency of the equipment when used for actual cooking tasks. Below the results of boiling 1 kg water in a conventional pan on a glass-ceramic range, in an electric kettle, and in the EffiCooker are shown. The initial water temperature is 15°C.

5.1.1 Ordinary pan

The heat is turned off when vapor bubbles penetrate the water surface, as observed through the transparent lid. Actually the heat could be turned off sooner and boiling still achieved, thereby making use of the heat stored in the hotplate. This would save some energy, but requires careful attention on the part of the user.

5.1.2 Electric kettle

Turns off automatically once water boils.

5.1.3 EffiCooker

Set to "Boil 9", "2 seconds". The cooker turns off after 2 seconds of boiling.

Table 10 shows the results of boiling 1 kg water. The cooking efficiency = the ratio of energy that ends up in the water to the total energy consumption is also shown.

Table 10. Boiling 1 kg water

	Conventional pan on range	**Electric kettle**	**EffiCooker**
Energy consumed	170 Wh	116 Wh	123 Wh
Time	13 minutes	4 minutes	7.5 minutes
Efficiency	58 %	85 %	80 %
Energy saving		54 Wh = 32 %	47 Wh = 28 %

Evidently the electric kettle performs better, considering energy as well as time; it saves 32% energy as compared to the ordinary pan. The EffiCooker takes about twice as long, and saves 28% energy. The main reason is the higher heating power of the electric kettle.

5.2 Soft-cooked eggs

This subject will be treated in some depth because it is an example of a rather critical process regarding time and temperature, and because it proves how efficiently and effortlessly it is handled by the EffiCooker.

The interior of an egg consists mainly of proteins, aside from water. When proteins are heated they first denature then coagulate to form a gel. The white and yolk consist of different proteins that coagulate at different temperatures; the proteins of the white coagulate at a lower temperature (62...65°C) than do those of the yolk (65...70°C) [6]. To cook eggs in the shell they are usually immersed in hot water for a certain time. Using boiling water is an easy way of attaining a constant, well-defined temperature. A lower water temperature might actually lead to better results, but it would be more difficult to control, and require a longer cooking time, too. Still another possibility is steaming, which is likely to be more energy efficient, because it doesn't involve heating a large amount of water.

To soft-cook an egg, i. e. to end up with a firm white and a runny yolk, the temperature at the white-yolk interface should ideally reach 65°C, according to the above coagulation temperatures. It is assumed that the rate of reaction is fast in comparison with ordinary cooking times. To make sure the white is fully set – at the risk that the surface of the yolk may have begun to thicken – one may select a slightly higher temperature, say, 67°C. Incidentally, destroying e. g. *Salmonella typhimurium* and *Staphylococcus aureus* in eggs requires approx. 76 and 87°C, respectively [8], so actually a runny yolk indicates that the egg may not be pathogen-free.

Achieving a rather precise temperature at a certain point in the egg is no trivial matter. The formula below gives the time t_{cooked} needed to obtain the temperature T_{yolk} at the outer boundary of the yolk, from the moment the egg is plunged into the hot water,

$$t_{cooked} = \frac{m^{\frac{2}{3}} c_p \rho^{\frac{1}{3}}}{k\pi^2 (\frac{4}{3}\pi)^{\frac{2}{3}}} \ln\left(0.76 \times \frac{T_{egg} - T_{water}}{T_{yolk} - T_{water}}\right) \text{ [s]}$$

T_{egg}	initial temperature of egg [°C]
T_{water}	(constant) temperature of water = surface temperature of egg [°C]
T_{yolk}	desired temperature at yolk outer boundary [°C]
m	mass (weight) of egg [g]
ρ	density of egg [g/cm^3]
c_p	specific heat of egg [J/(g·K)]
k	thermal conductivity of egg [W/(cm·K)]

The derivation involves solving the heat diffusion equation [9], and several simplifications are made; it is assumed that the egg is a homogeneous, spherical object, that the ratio of the amounts of white and yolk is constant, that there is no convection and no heat of reaction, that the thermal properties are constant, not temperature dependent, and the thermal properties used are those of the white, because that is where most of the heat is stored and transferred during cooking. Despite the approximations the formula proves quite useful. An important feature is that t_{cooked} is proportional to $m^{2/3}$, everything else being equal.

After the egg has been removed from the hot water, heat continues to diffuse toward the yolk. The egg should be chilled briefly then served immediately to limit the effect of such continued cooking.

Of course one may determine the cooking time experimentally. Having done so for one egg size it is a simple matter to extrapolate to a different size using the relation mentioned above

$$t_{cooked} \propto m^{2/3}$$

In the calculations of cooking times the following parameter values are used. T_{water} is chosen equal to the EffiCooker steaming temperature, 95°C; the egg thermal properties are taken from [9].

T_{egg} = 6°C

T_{water} = 95°C

T_{yolk} = 67°C

ρ = 1.038 g/cm^3

c_p = 3.7 J/(g·K)

k = 0.0054 W/(cm·K)

The cooking time t_{cooked} for a 50 g egg will be

$$t_{cooked} = \frac{m^{\frac{2}{3}} c_p \rho^{\frac{1}{3}}}{k\pi^2 (\frac{4}{3}\pi)^{\frac{2}{3}}} \ln\left(0.76 \times \frac{T_{egg} - T_{water}}{T_{yolk} - T_{water}}\right) \cong$$

$$\frac{50^{\frac{2}{3}} \times 3.7 \times 1.038^{\frac{1}{3}}}{0.0054\pi^2 (\frac{4}{3}\pi)^{\frac{2}{3}}} \ln\left(0.76 \times \frac{6-95}{67-95}\right) \cong 324\,\mathrm{s} = 5\,\mathrm{m}\;24\,\mathrm{s}$$

The cooking times for eggs of other sizes are calculated in the same way. Table 11 shows values for eggs of various sizes. The weights shown are the minimums allowed for the corresponding weight class, averaged over a dozen eggs [6]. The cooking time is seen to increase by 30 seconds when moving up one weight class.

Table 11. Cooking times for soft-cooked egg

U.S. weight class	**Weight** g	t_{cooked} **m:s**
Small	43	4:53
Medium	50	5:24
Large	57	5:53
Extra large	64	6:22

To get an impression of the precision needed regarding time and temperatures, Table 12 has been derived from the formula, for an egg of medium size. It shows the absolute partial derivative of each parameter with respect to T_{yolk}, i. e. the change that will lead to a change in T_{yolk} of 1°C. E. g. an increase in refrigerator temperature (T_{egg}) by 3°C will lead to T_{yolk} increasing by 1°C; this may be compensated by shortening the cooking time by 13 s. Going from T_{water} = 95°C to T_{water} = 100°C leads to a decrease in cooking time by about 45 seconds. Obviously a certain accuracy is required in determining and monitoring each parameter. Still, because eggs vary in shape and composition, in rare cases the results may not prove satisfactory.

Table 12. Required precision of egg cooking parameters

m	3	g
T_{egg}	3	°C
T_{water}	1.5	°C
t_{cooked}	13	s

There are dedicated egg cookers on the market. The simple type of egg cooker is "automatic" in the sense that it turns off once all the water has evaporated. An accurately measured amount of water must be poured into the egg cooker. The amount is taken from a table in the accompanying booklet, and it depends on how many eggs are to be cooked, etc. The mere fact that all the water must evaporate suggests that such a device cannot be very energy efficient. Besides it is quite difficult to achieve consistent results.

In the following we compare the conventional range with the EffiCooker preparing soft cooked eggs of size "extra large" (64 g).

5.2.1 Ordinary pan

In order to achieve a precise timing an ample amount of water is used, and the eggs immersed in it after it has been brought to a boil. The task could be done with less water, but timing would be more difficult.

An ordinary pan of capacity similar to the EffiCooker is filled with 1 kg water, enough to just cover the eggs. The pan is covered and the water brought to a boil at maximum heat setting (9) on a 150 mm cooking zone. The eggs are slipped in, the lid replaced, and the timer started. After one minute, when the water has returned to a rapid boil, the heat is turned down (to setting 4) to just keep the water boiling. One minute before the eggs are done the heat is turned off. After 6 minutes of immersion the eggs are taken up, briefly chilled, and served immediately.

5.2.2 EffiCooker

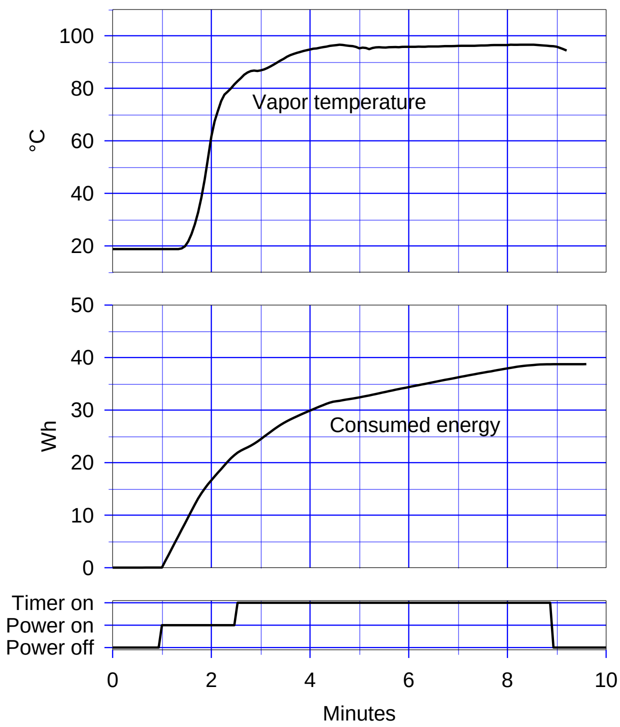

Figure 9. Steaming 2 soft-cooked eggs in EffiCooker

The eggs are placed in the cooker along with 50 g water, covered, "Steam 8", "6:30" are selected, and the power turned on. At the sound of the beep the eggs are removed, chilled briefly, and served.

The process is illustrated in the graphs of Figure 9. The vapor temperature inside the cooker, the electricity consumption, and the timer function are shown. Please note how the controller keeps the vapor temperature close to 95°C during cooking.

The results are compared in Table 13. Employing the EffiCooker results in a substantial saving of energy (142 Wh, or 78%) as well as time (11 minutes).

Table 13. Soft-cooking 2 eggs

	Boiling in conventional pan	**Steaming in EffiCooker**
Amount of water	1000 g (to cover eggs)	50 g
Energy consumed	181 Wh	39 Wh
Total time	19 minutes	8 minutes
Energy saving		142 Wh = 78 %

For the EffiCooker the theoretical fixed and running energy consumptions are calculated: the energy spent in heating the heat capacities of water and eggs, the energy for evaporation and the heat flow to the surroundings. The possible heat of reaction is ignored.

$$W_{water} = \frac{mc_p(T_h - T_l)}{3600} \cong \frac{0.05 \times 4200\,(100 - 15)}{3600} \cong 5\,\text{Wh}$$

$$W_{eggs} = \frac{mc_p(T_h - T_l)}{3600} \cong \frac{0.128 \times 3320(67 - 6)}{3600} \cong 7.2\,\text{Wh}$$

$$Q_{evap} = \dot{Q}_{evap} \cdot t \cong 4 \times \frac{8}{60} \cong 0.5\,\text{Wh}$$

$$Q_{surr} = \dot{Q}_{surr} \cdot t \cong 44 \times \frac{8}{60} \cong 6\,\text{Wh}$$

m	mass; for water: 0.05 kg; for eggs: 0.128 kg
c_p	specific heat; water: 4200 J/(kg·°C); eggs: 3320 J/(kg·°C)
T_l	initial, low, temperature: water: 15°C; eggs: 6°C
T_h	final, high, temperature; water: 100°C; eggs: 67°C
$\dot{Q}_{evap}$	running evaporation loss: 4 W (Measured energy losses, p. 23)
$\dot{Q}_{surr}$	running energy loss: 44 W (Table 8, p. 24)
t	total time [h]: 8 minutes = 8/60 h

Table 14 compares the calculated energy consumption with the actual, measured consumption. The two agree fairly well, the latter (39 W) exceeding the former (36 W) by about 8%. The table gives an impression of the various energy losses, the inner pan heat capacity clearly accounting for the greater part.

Table 14. Soft-cooking 2 eggs in EffiCooker. Theoretical and actual energy consumption

	Wh
Inner pan heat capacity (Table 3, p. 21)	17
Water heat capacity	5
Eggs heat capacity	7.2
Evaporation	0.5
Loss to surroundings	6
Total theoretical energy consumption	**36**
Total actual energy consumption	**39**

5.3 Boiling pasta

Dry pasta is cooked in boiling water to a standard called "al dente", meaning it should be tender but not too tender. During cooking it absorbs water corresponding to approximately 1.5 times its own weight. Some recipes require that salt and/or fat be added.

It is a persistent notion that pasta should be cooked in an overly large amount of rapidly boiling water, not covered, to keep it from sticking. For example, Joy of Cooking [5] states "7 quarts of rapidly boiling water for a pound of pasta", which corresponds to an amount of water that is 15 times that of pasta by weight. This looks like a striking example of squandering energy; using this method leads to an energy consumption more than five times greater than that of the EffiCooker. An experiment shows that excellent results may be obtained using much less water; about 3.5 times the weight of the pasta is enough to amply cover the pasta before cooking. In the case of long pastas (spaghetti) some more water may be needed to be able to gradually immerse the pasta as it softens. So from an energy conservation point of view one shouldn't use long pasta! We try three different cooking methods, two on an ordinary glass-ceramic hob, and one in the EffiCooker. The dry pasta at hand is of the "Fusilly" shape and labeled "Cooking time 9...11 minutes".

5.3.1 Joy of Cooking method

Bring 3000 g water to a rapid boil. Add 200 g dry pasta. Reduce heat to maintain rapid boil. Don't cover. Taste several times; when pasta is al dente turn heat off and remove the pasta from the water with a pasta scoop.

5.3.2 Ordinary careful method

Put 200 g dry pasta and 700 g water into the pan and cover. Turn the heat to maximum; when boiling start timer and reduce heat to maintain boil. After 9 minutes of boiling turn heat off. After 10 minutes scoop up pasta or use a colander.

5.3.3 EffiCooker method

Put 200 g dry pasta and 700 g water into the EffiCooker and cover. Select "Boil 7" and "10 m" and turn the power on. At the sound of the beep the pasta is ready. Hold the lid askew and drain the excess water from the pasta (no kitchen mitts necessary!). If the pasta is served in the cooker it will keep warm for a long time.

Table 15. Boiling 200 g pasta

	Joy of Cooking	**Ordinary careful**	**EffiCooker**
Amount of water	3000 g	700 g	700 g
Energy consumption	590 Wh	160 Wh	110 Wh
Time	24 minutes	20 minutes	21 minutes
Energy saving		430 Wh = 73 %	480 Wh = 81 %

The results in Table 15 show the substantial energy saving obtained with both an ordinary pan and the EffiCooker over the Joy of Cooking method. It is also evident that the EffiCooker saves 50 Wh, or 31%, compared to the ordinary careful method.

5.4 Steaming potatoes

Potatoes may be classified as waxy or mealy. The waxy type is suited for boiling, whereas the mealy one lends itself for mashing and baking. We will concentrate on boiling the waxy type. Medium size (about 100 g) mature potatoes need about 20 minutes of boiling to become tender. New potatoes may be done in a couple of minutes less, old ones or particularly large ones may require a couple of minutes more. Below we steam 1 kg potatoes on the range and in the EffiCooker.

5.4.1 Ordinary pan

The potatoes are placed in the pan along with 100 g water. The pan, covered, is placed on a 150 mm cooking zone (nominal power 1 kW) at maximum heat setting (9). After approx. 8.5 minutes steam begins issuing; the heat is reduced to setting 6, then 5, then 4, trying to maintain a reasonable emission of steam. After 29 minutes the potatoes are done; the heat is turned off 1 minute before that.

5.4.2 EffiCooker

Fill cooker with 1 kg potatoes and 100 g water, cover, select "Steam 8", set the time at 20 minutes, and turn on. At the sound of the beep drain the water from the potatoes (no oven mitts!) and serve. Figure 10 is a graph of the vapor temperature, energy consumption, and timer operation.

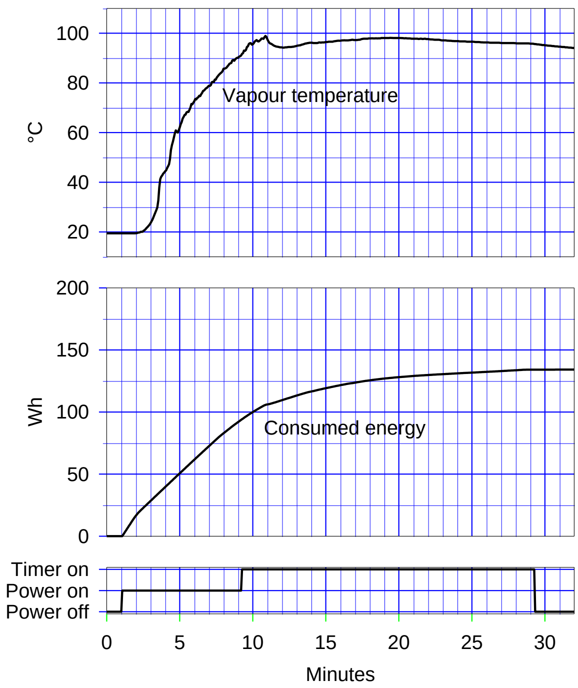

Figure 10. Steaming 1 kg potatoes in EffiCooker

In Table 16 the times and energy consumptions are compared. In the case of the EffiCooker there is an energy saving of 58 Wh, or 30%, whereas the time saving is negligible.

Table 16. Steaming 1 kg potatoes

	Ordinary pan	**EffiCooker**
Amount of water	100 g	100 g
Total time	29 minutes	28 minutes
Energy consumption	190 Wh	132 Wh
Energy saving		58 Wh = 30 %

The theoretical fixed and running energy consumptions are calculated for the case of the EffiCooker: the energy spent in heating the heat capacities of water and potatoes, the energy for evaporation and the heat flow to the surroundings. The possible heat of reaction is ignored.

$$W_{water} = \frac{mc_p(T_h - T_l)}{3600} \cong \frac{0.1 \times 4200(100-15)}{3600} \cong 10\,\text{Wh}$$

$$W_{potatoes} = \frac{mc_p(T_h - T_l)}{3600} \cong \frac{1 \times 3450(95-20)}{3600} \cong 72\,\text{Wh}$$

$$Q_{surr} = \dot{Q}_{surr} \cdot t \cong 44 \times \frac{28}{60} \cong 21\,\text{Wh}$$

$$Q_{evap} = \dot{Q}_{evap} \cdot t \cong 4 \times \frac{28}{60} \cong 2\,\text{Wh}$$

m	mass; for water: 0.1 kg; for potatoes: 1 kg
c_p	specific heat; water: 4200 J/(kg·°C); potatoes: 3450 J/(kg·°C)
T_l	initial, low, temperature: water: 15°C; potatoes: 20°C
T_h	final, high, temperature; water: 100°C; potatoes: 95°C
$\dot{Q}_{evap}$	running evaporation loss: 4 W (Measured energy losses, p. 23)
$\dot{Q}_{surr}$	running energy loss: 44 W (Table 8, p. 24)
t	total time [h]: 28 minutes = 28/60 h

Table 17 compares the calculated energy consumption with the actual, measured consumption. The actual consumption (132 Wh) is in fair agreement with the theoretical one (122 Wh); it exceeds it by about 8%. Evidently for a cooking task of this duration the running losses (evaporation and loss to surroundings) begin to make themselves felt.

Table 17. Steaming 1 kg potatoes in EffiCooker. Theoretical and actual energy consumption

	Wh
Inner pan heat capacity (Table 3, p. 21)	17
Water heat capacity	10
Potatoes heat capacity	72
Evaporation	2
Loss to surroundings	21
Total theoretical energy consumption	**122**
Total actual energy consumption	**132**

5.5 Boiling rice

Rice kernels, which have had only their husk removed (brown rice), consist of approx. 90% starch. The germ and bran account for the remaining 10%. Polished or white rice has had the bran and germ removed and so consists mostly of starch, mainly amylopectin and amylose. A substantial amount of vitamins, minerals, and fiber is in the bran and so is removed in the polishing process.

Medium- and short-grain (Japonica) rice tends to become sticky when boiled, whereas long-grain (Indica) rice is more likely to stay loose and fluffy, each grain remaining separate. This is due to the amylose-to-amylopectin ratio being higher in the long-grain species. There are various types of specialty rice on the market, e. g. Arborio, Valencia, Basmatic, Pecan, Jasmine, "wild rice", and many others.

The food industry supplies various types of preprocessed rice. E.g. parboiled (or converted) rice is a form of polished rice which cooks faster and in which a larger proportion of valuable nutrients from the bran is preserved.

When rice is boiled the starch is gelatinized then pasted, improving digestibility and flavor. In this process the starch absorbs a great deal of liquid. One may boil the rice in ample water, discarding the excess afterwards. However, energy as well as valuable soluble nutrients are wasted this way. So it is preferable to use just the right amount of water which will allow the grains to swell to capacity. Too much stirring should be avoided, as grains may be broken [6].

In the experiment below we boil ordinary, long-grain, loose rice .

5.5.1 Rice cooker

A rice cooker is a utensil that automatically controls the heat and timing. It is primarily meant for cooking rice, as the name implies, but may also be employed for other kinds of food. Once the user has loaded the ingredients into the rice cooker and turned the power on, the food is supposed to be cooked with no further attention.

Rice cookers come in various degrees of sophistication. A simple type is very popular, especially in Asian countries. It consists of an outer housing containing an electric hotplate and a removable inner bowl. The hotplate usually is laid out for two power levels: high power to heat and cook, and low power to keep the food warm once it has been cooked. The user initiates the process by moving a lever to "cook". A mechanical switching device senses the temperature of the bottom of the inner bowl and switches to "keep warm" once the temperature exceeds the boiling point of water by a certain amount, indicating that the excess water has boiled off. Thus the automatic timing is based on the time it takes water to partly be absorbed in the food, partly evaporate, so the more water is added, the longer the cooking time. Therefore it is important to correctly estimate and measure the required amount of water. Incidentally, the cooking time will also depend on the mains line voltage: the higher the voltage the shorter the cooking time, because higher voltage means higher power, which in turn means faster evaporation.

The power rating of the heating element must be sufficient for a reasonably fast heating of the food and water. As a consequence, when boiling commences at this same power level, it is rather rapid. Thus relatively much water is evaporated, resulting in a rather low energy efficiency, and a tendency to boiling over. Besides a crust may form at the bottom, where the rice is heated above the boiling point.

The Tefal Classic 2.0 L (Figure 5, p. 15, left) is representative of the simple type of rice cooker. Its labeled power rating is 450...530 W.

200 g ordinary, polished, long-grain rice, 500 g water, and 2 g salt are filled into the rice cooker. The switch is moved to the "cook" position. After about 13 minutes the lid must be placed askew to limit boiling over. After 23 minutes the rice cooker switches to "keep warm" and the rice is ready to serve. There is a crust or "cake" at the bottom.

5.5.2 EffiCooker

Put 200 g rice, 440 g water (= 2.2 times the amount of rice by weight), and 2 g salt into the EffiCooker. Select "Boil 7" and "20 m" and turn the power on. When the audible signal sounds the rice is ready to serve. No boiling over and no crust at the bottom.

Table 18. Boiling 200 g rice

	Tefal Classic 2.0L rice cooker	**EffiCooker**
Amount of water	500 g	440 g
Total time	23 minutes	30 minutes
Energy consumed	184 Wh	90 Wh
Energy saving		94 Wh = 51%

Table 18 shows that the rice cooker is faster than the EffiCooker by 7 minutes but uses about twice as much energy.

5.6 Scalding milk

Some recipes call for scalded (or boiled) milk, e. g. hot chocolate or yeast dough. When milk is heated to a temperature near the boiling point, a precipitate inevitably forms on the bottom of the pan. This is believed to be coagulated whey proteins; lactalbumin, for example, begins to coagulate at 66°C. This precipitate is liable to scorch unless a double boiler is used or the milk is stirred frequently.

If the heating takes place in an uncovered pan, a surface skin forms, possibly caused by a drying out of the surface of the milk. This skin probably also consists of coagulated proteins, in combination with fat and minerals. The skin, besides being unappetizing, may form a tight, steam proof film over the milk, causing it to foam and boil over [6].

The EffiCooker is well suited to scalding milk; it eliminates the above inconveniences. Selecting a low power range (Boil 3), no stirring is needed to avoid scorching. Consequently the lid may be in place all the time, so no skin is formed, and there is no boiling over. Once the timer has been set and the power has been switched on the milk is slowly heated to the boiling point and kept there for the selected time, without further user intervention. The inevitable precipitate is easily cleaned out afterwards.

5.7 Melting chocolate

Cocoa butter is the primary constituent in chocolate. It melts in the rather narrow range of 30 to 36°C. According to some sources, melting chocolate for candy dipping is a project with gloomy prospects. The weather conditions, the kitchen temperature, and the air humidity are all critical. The utensils must be absolutely dry. The grated chocolate must be heated very slowly in a double boiler over – not in – boiling water, to a temperature of 55°C. It must be stirred constantly, lest the cocoa butter separate out. Then the chocolate must cool to 31°C; a thermometer is indispensable. The purpose of this so-called "tempering" is to permit the cocoa butter to form beta crystals, which are more stable than alpha or gamma crystals. Chocolate that contains mainly beta crystals is less likely to develop *bloom* when stored, i. e. to form a grayish coating of recrystallized cocoa butter. The tendency to blooming may also be influenced by additives in the production process [5][6].

While this procedure may well be a little over-scrupulous, it may easily and effortlessly be carried out using the EffiCooker, dispensing with the double boiler as well as the thermometer, as proved by this experiment:

Figure 11. Melting chocolate

Figure 12. Marzipan centers

Figure 13. Chocolate covered marzipan

100 g of dark semisweet chocolate in whole squares, not grated, was placed in the cooker and the temperature set at 55°C. After about 20 minutes the chocolate had melted with no problems and no stirring, although it would probably have taken less time had

the chocolate been grated and/or stirred (Figure 11). The temperature setting was then lowered to 31°C, and after about 10 minutes some marzipan centers (Figure 12) were dipped, using a fork, and placed on a sheet of baking paper to cool. The result was very satisfactory (Figure 13), although there wasn't any opportunity to test the keeping qualities.

6 Testing Standards for Cooking Equipment

Most test procedures for cooktops are based on measuring the amount of energy required to raise a metal test block from room temperature to a specified temperature above room temperature, or to boil a specified amount of water [15][16].

Existing testing standards, as far as is known, don't facilitate the comparison of the energy consumption of an electric pan with that of an ordinary pan, nor the comparison of energy consumption when performing actual cooking tasks. In this treatment we resort to comparing actual cooking tasks.

7 Conclusion

Substantial energy savings in moist heat cooking may be achieved by employing an electric pan (i. e. a pan with integrated electric heating element) rather than an ordinary pan on a conventional range. The electric pan should be thermally insulated and it should be equipped with an "intelligent" controller and timer. A working prototype of a saucepan, dubbed the EffiCooker, has been constructed according to these guidelines.

The EffiCooker has demonstrated energy savings in the range from 28% to 81% compared to conventional equipment when performing ordinary cooking tasks.

Furthermore, the EffiCooker is very user friendly. Many cooking tasks, once initiated, are performed automatically without any further user attention. The EffiCooker also may replace many other kitchen appliances.

There is still room for improvement, though. The following topics should be investigated: Improved thermal insulation, reduced heat capacity, pressure cooking, improved controller, and a more attractive appearance.

8 Acknowledgment

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10 Appendix. Theoretical Energy Consumptions

The theoretical steady-state heat losses (running losses) are calculated for the EffiCooker, for a single-wall electric pan, and for a conventional pan on a range. First the convection losses are calculated then the radiation losses. We also calculate the energy needed to heat the heat capacities (thermal masses) of the three kinds of pan (fixed losses).

A brief description of the calculating procedure follows.

10.1 Procedure

10.1.1 Convection heat losses

The convection losses are calculated according to the theory of natural convection, based on the dimensionless Grashof, Prandtl, Rayleigh, and Nusselt numbers, *Gr, Pr, Ra,* and *Nu* [7]. The Grashof number *Gr* governs the flow regime, i. e. whether the flow is laminar or turbulent. For air it depends mainly on the temperatures and on the "characteristic length" δ [m] of the geometry.

$$Gr = \frac{g\beta(T_h - T_l)\delta^3}{\nu^2}$$

g	gravitational acceleration = 9.8 m/s^2
β	coefficient of volume expansion for air [K^{-1}]
ν	kinematic viscosity of air [m^2/s]
k	thermal conductivity of air [W/(m·K)]
A	heat transfer surface area [m^2]
T_h	the high temperature [K] from which heat is transferred to
T_l	the low temperature [K]
T_{ave}	average temperature = $(T_h + T_l) / 2$ [K]

For a vertical plate, for example, δ is equal to the height of the plate, whereas for an air gap, such as the space between the two vertical walls of a dual-wall vessel, δ is equal to the thickness of the gap.

The coefficient of volume expansion β is set equal to 1/T, the value for ideal gases. The kinematic viscosity ν and the thermal conductivity k are looked up in a table as a function of the temperature. The Prandtl number *Pr* for air is close to 0.7; it is also a table value, slightly dependent on temperature. In all cases the average temperature T_{ave} is used.

The Raleigh number *Ra* is the product of the Grashof and Prandtl numbers

$$Ra = GrPr$$

The Nusselt number *Nu* represents the enhancement of heat transfer due to natural convection (*Nu* > 1) relative to pure conduction (*Nu* = 1). The Nusselt number is a function mainly of the Raleigh number and of the geometry, and there are separate empirical formulae for various geometries. For example, for a vertical surface, this rather elaborate formula applies

$$Nu = \left(0.825 + \frac{0.387 Ra^{\frac{1}{6}}}{\left(1 + (\frac{0.492}{Pr})^{\frac{9}{16}}\right)^{\frac{8}{27}}} \right)^2$$

Another example is the following formula, which is valid for a vertical enclosure, like the air space between the inner and outer side walls of a dual-wall vessel, provided that $0.5 < Pr < 2$ and $2000 < Ra < 2 \times 10^5$

$$Nu = 0.197\, Ra^{\frac{1}{4}} (\frac{\delta}{H})^{\frac{1}{9}}$$

In this case H [m] is the height and δ [m] is the thickness of the air gap.

Having determined the Nusselt number it is relatively easy to calculate the convective heat flow

$$\dot{Q}_{conv} = \frac{Nu\, k\, A (T_h - T_l)}{\delta} \text{ [W]}$$

10.1.2 Radiation heat losses

The radiated heat transfer involves simpler calculations than does the convective heat [7]. We consider the heat transfer rate from a surface at temperature T_h to a surface at temperature T_l, the surfaces having diffuse and gray radiation properties.

A surface of area A and emissivity ε that radiates to the surroundings is an example of the case "small object in large cavity". The emissivity and area of the surroundings may be disregarded, and the formula becomes

$$\dot{Q}_{rad} = \sigma\, \varepsilon\, A (T_h^{\ 4} - T_l^{\ 4}) \text{ [W]}$$

The radiated heat transfer rate between two parallel surfaces of equal area A and emissivity ε across a relatively narrow air gap is

$$\dot{Q}_{rad} = \frac{\sigma\, \varepsilon\, A (T_h^{\ 4} - T_l^{\ 4})}{2 - \varepsilon} \text{ [W]}$$

σ Stefan-Boltzmann constant = 5.67×10^{-8} [W/(m^2 K^4)]

ε emissivity

The emissivity ε is taken to be (Table 2, p. 20)

$\varepsilon_{stainless\ steel}$ = 0.3 for the stainless steel of the pans

ε_{glass} = 0.8 for the glass material of the transparent lids

10.1.3 Heat capacities

The energy needed to raise the temperature of a solid object from T_l to T_h may be expressed as

$$W = \frac{mc_p(T_h - T_l)}{3600} \text{ [Wh]}$$

m mass of object [kg]

c_p specific heat of object [J/(kg·K)]

T_l low (start) temperature of object [°C]

T_h high (final) temperature object [°C]

The energies needed to heat the heat capacities of the pans and hotplate (fixed energy losses) will be calculated using these specific heats (see Table 2, p. 20):

c_{glass} = 800 J/(kg·K) for the transparent lids

$c_{stainless\ steel}$ = 470 J/(kg·K) for the stainless steel material of the pans

$c_{glass\ ceramic}$ = 800 J/(kg·K) for the range cooking surface

c_{bead} = 1700 J/(kg·K) for the silicone bead sealing inner and outer pan

10.2 EffiCooker heat loss

Figure 7 (p. 21) is a simplified sketch of the double-walled pan. The heat losses are labeled $\dot{Q}_{top}$, $\dot{Q}_{side}$, and $\dot{Q}_{bottom}$, respectively. The dimensions are as follows (Table 1, p. 19)

D_{in} = 175 mm = 0.175 m

D_{out} = 200 mm = 0.2 m

H_{in} = 95 mm = 0.095 m

H_{out} = 135 mm = 0.135 m

Air gap in cover = 10 mm = 0.01 m

Air gap at sides and bottom = 12 mm = 0.012 m

We consider the case of *steaming*, hence the shallow layer of water; the inner top and side temperatures are 95°C, and the bottom temperature is 100°C. The surrounding temperature T_{amb} is 20°C.

$$T_{top,in} = T_{side,in} = 95\text{ °C} \cong 368.2\text{ K}$$

$$T_{bottom,in} = 100\text{ °C} \cong 373.2\text{ K}$$

$$T_{amb} = 20\text{ °C} \cong 293.2\text{ K}$$

The three heat flows each include a convection and a radiation component. The calculations for a double-walled pot are rather involved because for each of the three heat flows the flow across the air gap must equal the flow from the outer wall to the surroundings:

$$\dot{Q}_{top} = \dot{Q}_{top,gap,conv} + \dot{Q}_{top,gap,rad} = \dot{Q}_{top,surr,conv} + \dot{Q}_{top,surr,rad}$$

$$\dot{Q}_{side} = \dot{Q}_{side,gap,conv} + \dot{Q}_{side,gap,rad} = \dot{Q}_{side,surr,conv} + \dot{Q}_{side,surr,rad}$$

$$\dot{Q}_{bottom} = \dot{Q}_{bottom,gap,conv} + \dot{Q}_{bottom,gap,rad} = \dot{Q}_{bottom,surr,conv} + \dot{Q}_{bottom,surr,rad}$$

In the following calculations the temperatures $T_{top,out}$, $T_{side,out}$, and $T_{bottom,out}$, have been fitted to achieve this.

10.2.1 Top air gap

10.2.1.1 Convection through top air gap

We do the calculations as if the lid were the same diameter as the outer pan, D_{out} = 0.2 m, in order to approximate all of the upwardly exposed area.

$$A = \frac{\pi}{4} \times {D_{out}}^2 \cong \frac{\pi}{4} \times 0.2^2 \cong 0.0314\,\mathrm{m}^2$$

$$T_{top,in} = 95\ °\mathrm{C} \cong 368.2\ \mathrm{K}$$

$$T_{top,out} = 53.5\ °\mathrm{C} \cong 326.6\ \mathrm{K}$$

$$T_{ave} = \frac{T_{top,in} + T_{top,out}}{2} \cong \frac{368.2 + 326.6}{2} \cong 347.4\ \mathrm{K}$$

$$\delta = 0.01\,\mathrm{m}$$

At temperature T_{ave} we look up these table values

$$k \cong 0.0295\ \mathrm{W/(m \cdot K)}$$

$$\nu \cong 2.03 \times 10^{-5}\ \mathrm{m^2/s}$$

$$Pr \cong 0.707$$

For a horizontal enclosure with the hot surface at the bottom

$$Gr = \frac{g\beta(T_{top,in} - T_{top,out})\delta^3}{\nu^2} \cong \frac{9.8 \frac{1}{347.4}(368.2 - 326.6)\, 0.01^3}{(2.03 \times 10^{-5})^2} \cong 2830$$

$$Ra = Gr\, Pr \cong 2830 \times 0.707 \cong 2000$$

For 0.5 < Pr < 2 and 1700 < Ra < 7000 this formula for Nu applies

$$Nu = 0.059 Ra^{0.4} \cong 0.059 \times 2000^{0.4} \cong 1.23$$

$$\dot{Q}_{top,gap,conv} = \frac{Nu\, k\, A\,(T_{top,in} - T_{top,out})}{\delta} \cong$$

$$\frac{1.23 \times 0.0295 \times 0.0314\,(368.2 - 326.6)}{0.01} \cong 4.75\ \mathrm{W}$$

10.2.1.2 Radiation through top air gap

$$\dot{Q}_{top,gap,rad} = \frac{\sigma\, \varepsilon\, A\,({T_{top,in}}^4 - {T_{top,out}}^4)}{2 - \varepsilon} \cong$$

$$\frac{5.67 \times 10^{-8} \times 0.8 \times 0.0314 \times (368.2^4 - 326.6^4)}{2 - 0.8} \cong 8.3\ \mathrm{W}$$

10.2.1.3 Total heat loss through top air gap

$$\dot{Q}_{top,gap} = \dot{Q}_{top,gap,conv} + \dot{Q}_{top,gap,rad} \cong 4.75 + 8.3 \cong 13\,\mathrm{W}$$

10.2.2 Top to surroundings

10.2.2.1 Convection from top to surroundings

$$T_{ave} = \frac{T_{top,out} + T_{amb}}{2} \cong \frac{326.6 + 293.2}{2} \cong 309.9\,\mathrm{K}$$

At this temperature we get these table values:

$$k = 0.0268\,\mathrm{W/(m \cdot K)}$$

$$\nu = 1.67 \times 10^{-5}\,\mathrm{m^2/s}$$

$$Pr = 0.711$$

For a horizontal surface the characteristic length δ is defined as follows, where A is the area and p is the perimeter of the surface

$$\delta = \frac{A}{p} = \frac{\pi D_{out}^{\;2}}{4\pi D_{out}} = \frac{D_{out}}{4} \cong \frac{0.2}{4} \cong 0.05\,\mathrm{m}$$

$$Gr = \frac{g\beta(T_{top,out} - T_{env})\delta^3}{\nu^2} \cong \frac{9.8\frac{1}{309.9}(326.6 - 293.2)\,0.05^3}{(1.67 \times 10^{-5})^2} \cong 4.76 \times 10^5$$

$$Ra = Gr\,Pr \cong 4.76 \times 10^5 \times 0.711 \cong 3.38 \times 10^5$$

Nu for a hot horizontal surface facing upwards and $10^4 < Ra < 10^7$:

$$Nu = 0.54\,Ra^{1/4} \cong 0.54 \times (3.38 \times 10^5)^{1/4} \cong 13$$

We can now compute the convective heat flow

$$\dot{Q}_{top,surr,conv} = \frac{Nu\,k\,A\,(T_{top,out} - T_{amb})}{\delta} \cong$$

$$\frac{13 \times 0.0268 \times 0.0314\,(326.6 - 293.2)}{0.05} \cong 8.33\,\mathrm{W}$$

10.2.2.2 Radiation from top to surroundings

$$\dot{Q}_{top,surr,rad} = \sigma\,\varepsilon\,A\,(T_{top,out}^{\;4} - T_{amb}^{\;4}) \cong$$

$$5.67 \times 10^{-8} \times 0.8 \times 0.0363 \times (326.8^4 - 293.2^4) \cong 6.62\,\mathrm{W}$$

10.2.2.3 Total heat loss from top to surroundings

The total heat flow from top to surroundings is the sum of the convection and the radiation heat flows

$$\dot{Q}_{top,surr} = \dot{Q}_{top,surr,conv} + \dot{Q}_{top,surr,rad} \cong 7.35 + 5.7 \cong 13\,\mathrm{W}$$

Please note that $\dot{Q}_{top,gap} \cong \dot{Q}_{top,surr} \cong 13\,\mathrm{W}$. This is a result of the fitting of $T_{top,out} = 53.5\,^{\circ}\mathrm{C}$

10.2.3 Side air gap

10.2.3.1 Convection through side air gap

$$T_{side,in} = 95\,°\mathrm{C} \cong 368.2\,\mathrm{K}$$

$$T_{side,out} = 47.9\,°\mathrm{C} \cong 321.1\,\mathrm{K}$$

$$T_{ave} = \frac{T_{side,in} + T_{side,out}}{2} \cong \frac{368.2 + 321.1}{2} \cong 344.6\,\mathrm{K}$$

$$\delta = 12\,\mathrm{mm} = 0.012\,\mathrm{m}$$

At temperature T_{ave} we get these table values

$$k \cong 0.0293\,\mathrm{W/(m\cdot K)}$$

$$\nu \cong 2.01 \times 10^{-5}\,\mathrm{m^2/s}$$

$$Pr \cong 0.707$$

The area is taken to be the mean of the inner and outer area

$$A = \pi \frac{D_{out} + D_{in}}{2} H \cong \pi \frac{0.2 + 0.175}{2} 0.135 \cong 0.0795\,\mathrm{m}^2$$

$$Gr = \frac{g\beta(T_{side,in} - T_{side,out})\delta^3}{\nu^2} \cong \frac{9.8 \frac{1}{344.6}(368.2 - 321.1)\,0.012^3}{(2.01 \times 10^{-5})^2} \cong 5751$$

$$Ra = GrPr \cong 5751 \times 0.707 \cong 4066$$

As $0.5 < Pr < 2$ and $2000 < Ra < 2 \times 10^5$ we use the following formula for Nu

$$Nu = 0.197 \times Ra^{1/4} \times (\frac{\delta}{H})^{1/9} \cong 0.197 \times 4066^{1/4} (\frac{0.012}{0.135})^{1/9} \cong 1.2$$

$$\dot{Q}_{side,gap,conv} = \frac{Nu\,k\,A(T_{side,in} - T_{side,out})}{\delta} \cong$$
$$\frac{1.2 \times 0.0293 \times 0.0795(368.2 - 321.1)}{0.012} \cong 11\,\mathrm{W}$$

10.2.3.2 Radiation through side air gap

$$\dot{Q}_{side,gap,rad} = \frac{\sigma\,\varepsilon\,A(T_{side,in}{}^4 - T_{side,out}{}^4)}{2 - \varepsilon} \cong$$
$$\frac{5.67 \times 10^{-8} \times 0.3 \times 0.0795 \times (368.2^4 - 321.1^4)}{2 - 0.3} \cong 6.16\,\mathrm{W}$$

10.2.3.3 Total heat loss through side air gap

$$\dot{Q}_{side,gap} = \dot{Q}_{side,gap,conv} + \dot{Q}_{side,gap,rad} \cong 11 + 6.16 \cong 17.2\,\mathrm{W}$$

10.2.4 Side to surroundings

10.2.4.1 Convection from side to surroundings

$$T_{side,out} = 47.9\,°\mathrm{C} \cong 321.1\,\mathrm{K}$$

$$T_{amb} = 20\,°\mathrm{C} \cong 293.2\,\mathrm{K}$$

$$T_{ave} = \frac{T_{side,out} + T_{amb}}{2} \cong \frac{321.1 + 293.2}{2} \cong 307.1\,\mathrm{K}$$

At this temperature we get the following table values

$$k \cong 0.0266\,\mathrm{W/(m \cdot K)}$$

$$\nu \cong 1.64 \times 10^{-5}\ \mathrm{m^2/s}$$

$$Pr \cong 0.712$$

The area of heat transfer becomes

$$A = \pi\, D_{out} H \cong \pi\, 0.2 \times 0.135 \cong 0.0848\ \mathrm{m^2}$$

$$Gr = \frac{g\beta (T_{side,out} - T_{amb})\delta^3}{\nu^2} \cong \frac{9.8 \frac{1}{307.1}(321.1 - 293.2)\, 0.135^3}{(1.64 \times 10^{-5})^2} \cong 8.13 \times 10^6$$

$$Ra = GrPr \cong 8.13 \times 10^6 \times 0.712 \cong 5.78 \times 10^6$$

The side of the pan can be treated as a plane vertical surface, provided that

$$D > \frac{35H}{Gr^{1/4}}$$

$$0.2 > \frac{35 \times 0.135}{(8.13 \times 10^6)^{1/4}} \cong 0.09$$

The condition is clearly met, so *Nu* may be calculated using the formula for a plane vertical surface

$$Nu = \left(0.825 + \frac{0.387 Ra^{\frac{1}{6}}}{\left(1 + (\frac{0.492}{Pr})^{\frac{9}{16}}\right)^{\frac{8}{27}}} \right)^2 \cong \left(0.825 + \frac{0.387 \times (5.78 \times 10^6)^{\frac{1}{6}}}{\left(1 + (\frac{0.492}{0.712})^{\frac{9}{16}}\right)^{\frac{8}{27}}} \right)^2 \cong 26.7$$

$$\dot{Q}_{side,surr,conv} = \frac{Nu\, k\, A (T_{side,out} - T_{amb})}{\delta} \cong \frac{26.7 \times 0.0266 \times 0.0848 (321.1 - 293.2)}{0.135} \cong 12.5\,\mathrm{W}$$

10.2.4.2 Radiation from side to surroundings

$$\dot{Q}_{side,surr,rad} = \sigma\varepsilon A (T_{side,out}{}^4 - T_{amb}{}^4) \cong 5.67 \times 10^{-8} \times 0.3 \times 0.0848 (321.1^4 - 293.2^4) \cong 4.67\,\mathrm{W}$$

10.2.4.3 Total heat loss from side to surroundings

$$\dot{Q}_{side,surr} = \dot{Q}_{side,surr,conv} + \dot{Q}_{side,surr,rad} \cong 12.5 + 4.67 \cong 17.2\,\mathrm{W}$$

We note again that $\dot{Q}_{side,gap} \cong \dot{Q}_{side,surr} \cong 17.2\,\mathrm{W}$. This is a result of fitting $T_{side,out} = 47.9\,°\mathrm{C}$

10.2.5 Bottom air gap

10.2.5.1 Convection through bottom air gap

$$A = \frac{\pi}{4} \times D_{out}^{\ 2} \cong \frac{\pi}{4} \times 0.2^2 \cong 0.0314\,\mathrm{m}^2$$

$$T_{bottom,in} = 100\ °\mathrm{C} \cong 373.2\,\mathrm{K}$$

$$T_{bottom,out} \cong 54.5\,°\mathrm{C} \cong 327.6\ \mathrm{K}$$

$$T_{ave} = \frac{T_{bottom,in} + T_{bottom,out}}{2} \cong \frac{373.2 + 327.6}{2} \cong 350.4\ \mathrm{K}$$

$$\delta = 12\,\mathrm{mm} = 0.012\,\mathrm{m}$$

At temperature T_{ave} we look up this table value

$$k = 0.03\,\mathrm{W/(m \cdot K)}$$

For a horizontal enclosure with the hot surface at the top

$$Nu = 1$$

that is, there is no convection; heat transfer is by pure conduction.

$$\dot{Q}_{bottom,gap,conv} = \frac{Nu\ k\ A\,(T_{bottom,in} - T_{bottom,out})}{\delta} \cong$$

$$\frac{1 \times 0.03 \times 0.0314\,(373.2 - 327.6)}{0.012} \cong 3.54\,\mathrm{W}$$

10.2.5.2 Radiation through bottom air gap

$$\dot{Q}_{bottom,gap,rad} = \frac{\sigma\,\varepsilon\,A\,(T_{bottom,in}^{\ \ 4} - T_{bottom,out}^{\ \ 4})}{2 - \varepsilon} \cong$$

$$\frac{5.67 \times 10^{-8} \times 0.3 \times 0.0314 \times (373.2^4 - 327.6^4)}{2 - 0.3} \cong 2.47\,\mathrm{W}$$

10.2.5.3 Total heat loss through bottom air gap

$$\dot{Q}_{bottom,gap} = \dot{Q}_{bottom,gap,conv} + \dot{Q}_{bottom,gap,rad} \cong 3.54 + 2.47 \cong 6\,\mathrm{W}$$

10.2.6 Bottom to surroundings

10.2.6.1 Convection from bottom to surroundings

$$T_{ave} = \frac{T_{bottom,out} + T_{amb}}{2} \cong \frac{327.6 + 293.2}{2} \cong 310.4\ \mathrm{K}$$

At this temperature we get these table values:

$$k \cong 0.0269\,\mathrm{W/(m\cdot K)}$$

$$\nu \cong 1.67\times10^{-5}\ \mathrm{m^2/s}$$

$$Pr \cong 0.711$$

For a horizontal surface the characteristic length δ is defined as follows, where A is the area and p is the perimeter of the surface:

$$\delta = \frac{A}{p} = \frac{\pi D_{out}^{\ 2}}{4\pi D_{out}} = \frac{D_{out}}{4} \cong \frac{0.2}{4} \cong 0.05\,\mathrm{m}$$

$$Gr = \frac{g\beta(T_{bottom,out} - T_{amb})\delta^3}{\nu^2} \cong \frac{9.8\frac{1}{310.4}(327.6-293.2)\,0.05^3}{(1.67\times10^{-5})^2} \cong 4.86\times10^5$$

$$Ra = GrPr \cong 4.86\times10^5 \times 0.711 \cong 3.46\times10^5$$

For a hot surface facing downward and $10^5 < Ra < 10^{11}$, Nu is calculated like this:

$$Nu = 0.27\,Ra^{1/4} \cong 0.27(3.46\times10^5)^{1/4} \cong 6.55$$

We can then compute the convective heat flow:

$$\dot{Q}_{bottom,surr,conv} = \frac{Nu\,k\,A(T_{bottom,out} - T_{amb})}{\delta} \cong$$
$$\frac{6.55\times0.0269\times0.0314(327.6-293.2)}{0.05} \cong 3.81\,\mathrm{W}$$

10.2.6.2 Radiation from bottom to surroundings

$$\dot{Q}_{bottom,surr,rad} = \sigma\,\varepsilon\,A(T_{bottom,out}^{\ 4} - T_{amb}^{\ 4}) \cong$$
$$5.67\times10^{-8}\times0.3\times0.0314\times(327.6^4 - 293.2^4) \cong 2.21\,\mathrm{W}$$

10.2.6.3 Total heat loss from bottom to surroundings

$$\dot{Q}_{bottom,surr} = \dot{Q}_{bottom,surr,conv} + \dot{Q}_{bottom,surr,rad} \cong 3.81 + 2.21 \cong 6\,\mathrm{W}$$

$T_{bottom,out}$ has been fitted to obtain $\dot{Q}_{bottom,gap} \cong \dot{Q}_{bottom,surr} \cong 6\,\mathrm{W}$.

10.2.7 Total heat loss

$$\dot{Q}_{tot} = \dot{Q}_{top} + \dot{Q}_{side} + \dot{Q}_{bottom} \cong 13 + 17.2 + 6 \cong 36\,\mathrm{W}$$

10.2.8 Heat capacities

The energies to be stored in the inner lid, inner pan, sealing bead, and heater (fixed energies), are calculated.

$$W_{lid} = \frac{mc_p(T_h - T_l)}{3600} \cong \frac{0.4\times800(95-20)}{3600} \cong 6.7\ \mathrm{Wh}$$

$$W_{pan} \cong \frac{0.41 \times 470(95-20)}{3600} \cong 4\,\mathrm{Wh}$$

$$W_{bead} \cong \frac{0.13 \times 1700(95-20)}{3600} \cong 4.6\,\mathrm{Wh}$$

$$W_{heater} \cong \frac{0.125 \times 470(100-20)}{3600} \cong 1.3\,\mathrm{Wh}$$

The silicone sealing bead is considered part of the inner pan:

$$W_{pan,tot} = W_{pan} + W_{bead} \cong 4 + 4.6 \cong 8.6\ \mathrm{Wh}$$

$$W_{total} = W_{lid} + W_{pan,tot} + W_{heater} \cong 6.7 + 8.6 + 1.3 \cong 16.6\ \mathrm{Wh}$$

Evidently a rather large part of the energy is due to the lid and the silicone sealing bead: about 11 out of 17 Wh. This is caused by the relatively large specific heats of glass and silicone rubber. At least the sealing bead would be eliminated in a production model.

10.3 Simple electric pan heat loss

The simplified geometry is depicted in Figure 8, p. 22. The dimensions are as follows (Table 1, p. 19)

D = 175 mm = 0.175 m

H = 110 mm = 0.11 m

We again consider the case of *steaming*; the top and side temperatures are 95°C, and the bottom temperature is 100°C. The surrounding temperature T_{amb} is 20°C.

$$T_{top} = T_{side} = 95\ °\mathrm{C} \cong 368.2\ \mathrm{K}$$

$$T_{bottom} = 100\ °\mathrm{C} \cong 373.2\ \mathrm{K}$$

$$T_{amb} = 20\ °\mathrm{C} \cong 293.2\ \mathrm{K}$$

Three heat flows are depicted, each including a convection and a radiation component.

$$\dot{Q}_{top} = \dot{Q}_{top,conv} + \dot{Q}_{top,rad}$$

$$\dot{Q}_{side} = \dot{Q}_{side,conv} + \dot{Q}_{side,rad}$$

$$\dot{Q}_{bottom} = \dot{Q}_{bottom,conv} + \dot{Q}_{bottom,rad}$$

Each of the six heat flow components is calculated separately.

10.3.1 Top

10.3.1.1 Convection from top

$$T_{ave} = \frac{T_{top} + T_{amb}}{2} \cong \frac{368.2 + 293.2}{2} \cong 330.7\,\mathrm{K}$$

At the temperature T_{ave} = 330.7 K we get these table values:

$$k \cong 0.0283\,\mathrm{W/(m \cdot K)}$$

$$\nu \cong 1.87\times10^{-5}\ \mathrm{m^2/s}$$

$$Pr = 0.709$$

For a horizontal surface the characteristic length δ is defined as follows, where *A* is the area and *p* is the perimeter of the surface:

$$\delta = \frac{A}{p} = \frac{\pi D_{out}{}^2}{4\pi D_{out}} = \frac{D}{4} = \frac{0.175}{4} \cong 0.0438\,\mathrm{m}$$

$$Gr = \frac{g\beta(T_{top,out} - T_{env})\delta^3}{\nu^2} \cong \frac{9.8\dfrac{1}{330.7}(368.2 - 293.2)\,0.0438^3}{(1.87\times10^{-5})^2} \cong 5.34\times10^5$$

$$Ra = Gr\,Pr \cong 5.34\times10^5 \times 0.709 \cong 3.78\times10^5$$

Nu is calculated like this for $10^4 < \mathrm{Ra} < 10^7$:

$$Nu = 0.54\,Ra^{1/4} \cong 0.54\times(3.78\times10^5)^{1/4} \cong 13.4$$

We can then compute the top convective heat flow:

$$\dot{Q}_{top,conv} = \frac{Nu\,k\,A(T_{top} - T_{amb})}{\delta} \cong \frac{13.4\times0.0283\times0.0241\,(368.2 - 293.2)}{0.0438} \cong 15.6\,\mathrm{W}$$

10.3.1.2 Radiation from top

$$\dot{Q}_{top,rad} =$$

$$\sigma\,\varepsilon\,A(T_{top}{}^4 - T_{amb}{}^4) \cong 5.67\times10^{-8}\times0.8\times0.0241(368.2^4 - 293.2^4) \cong 12\,\mathrm{W}$$

10.3.1.3 Total heat loss from top

$$\dot{Q}_{top} = \dot{Q}_{top,conv} + \dot{Q}_{top,rad} \cong 15.6 + 12 \cong 27.6\,\mathrm{W}$$

10.3.2 Side

10.3.2.1 Convection from side

$$T_{ave} = \frac{T_{side} + T_{amb}}{2} \cong \frac{368.2 + 293.2}{2} \cong 330.7\ \mathrm{K}$$

At this temperature we get these table values (same as above):

$$k \cong 0.0283\,\mathrm{W/(m\cdot K)}$$

$$\nu \cong 1.87\times10^{-5}\ \mathrm{m^2/s}$$

$$Pr \cong 0.709$$

The side of the pot can be treated as a plane vertical surface, provided that

$$D > \frac{35H}{Gr^{1/4}}$$

$$0.175 > \frac{35\times0.11}{(8.48\times10^6)^{1/4}} \cong 0.07$$

This condition is clearly met. The characteristic length δ is then equal to *H*.

$$Gr = \frac{g\beta(T_{side} - T_{amb})\delta^3}{\nu^2} \cong \frac{9.8\frac{1}{330.7}(368.2 - 293.2)\,0.11^3}{(1.87\times10^{-5})^2} \cong 8.48\times10^6$$

$$Ra = Gr\,Pr \cong 8.48\times10^6 \times 0.709 \cong 6.01\times10^6$$

For $10^4 < Ra < 10^{13}$ Nu is calculated according to this formula

$$Nu = \left(0.825 + \frac{0.387 Ra^{\frac{1}{6}}}{\left(1 + (\frac{0.492}{Pr})^{\frac{9}{16}}\right)^{\frac{8}{27}}}\right)^2 \cong \left(0.825 + \frac{0.387\times(6.01\times10^6)^{\frac{1}{6}}}{\left(1 + (\frac{0.492}{0.709})^{\frac{9}{16}}\right)^{\frac{8}{27}}}\right)^2 \cong 27$$

We can then compute the convective heat flow:

$$\dot{Q}_{side,conv} =$$
$$\frac{Nu\,k\,A(T_{top} - T_{amb})}{\delta} \cong \frac{27\times0.0283\times0.0605(368.2 - 293.2)}{0.11} \cong 31.6\,\text{W}$$

10.3.2.2 Radiation from side

$$\dot{Q}_{side,rad} = \sigma\,\varepsilon\,A(T_{top}{}^4 - T_{amb}{}^4) \cong$$
$$5.67\times10^{-8}\times0.3\times0.0605(368.2^4 - 293.2^4) \cong 11.3\,\text{W}$$

10.3.2.3 Total heat loss from side

$$\dot{Q}_{side} = \dot{Q}_{side,conv} + \dot{Q}_{side,rad} = 31.6 + 11.3 \cong 42.9\,\text{W}$$

10.3.3 Bottom

10.3.3.1 Convection from bottom

$$T_{ave} = \frac{T_{bottom} + T_{amb}}{2} \cong \frac{373.2 + 293.2}{2} \cong 333.2\ \text{K}$$

At this temperature we get these table values:

$$k = 0.0285\,\text{W/(m}\cdot\text{K)}$$

$$\nu = 1.89\times10^{-5}\ \text{m}^2\text{/s}$$

$$Pr = 0.708$$

For a horizontal surface the characteristic length δ is defined as follows, where *A* is the area and *p* is the perimeter of the surface:

$$\delta = \frac{A}{p} = \frac{\pi D_{out}{}^2}{4\pi D_{out}} = \frac{D}{4} \cong \frac{0.175}{4} \cong 0.0438\,\text{m}$$

$$Gr = \frac{g\beta(T_{top,out} - T_{amb})\delta^3}{\nu^2} \cong \frac{9.8\frac{1}{333.2}(373.2 - 293.2)\, 0.0438^3}{(1.89\times 10^{-5})^2} \cong 5.51\times 10^5$$

$$Ra = Gr\, Pr \cong 5.51\times 10^5 \times 0.708 \cong 3.9\times 10^5$$

For a hot surface facing downward and $10^5 < Ra < 10^{11}$, Nu is calculated like this:

$$Nu = 0.27\, Ra^{1/4} \cong 0.27 \times (3.9\times 10^5)^{1/4} \cong 6.75$$

We can then compute the bottom convective heat flow:

$$\dot{Q}_{bottom,conv} = \frac{Nu\, k\, A(T_{bottom} - T_{amb})}{\delta} \cong$$
$$\frac{6.75\times 0.0285\times 0.0241(373.2 - 293.2)}{0.0438} \cong 8.46\,\mathrm{W}$$

10.3.3.2 Radiation from bottom

$$\dot{Q}_{bottom,rad} =$$
$$\sigma\, \varepsilon\, A(T_{top}{}^4 - T_{amb}{}^4) \cong 5.67\times 10^{-8} \times 0.3\times 0.0241(373.2^4 - 293.2^4) \cong 4.91\,\mathrm{W}$$

10.3.3.3 Total heat loss from bottom

$$\dot{Q}_{bottom} = \dot{Q}_{bottom,conv} + \dot{Q}_{bottom,rad} \cong 8.46 + 4.91 \cong 13.4\,\mathrm{W}$$

10.3.4 Total heat loss

The total heat loss of the simple electric pan is the sum of the top, side, and bottom heat flows

$$\dot{Q}_{tot} = \dot{Q}_{top} + \dot{Q}_{side} + \dot{Q}_{bottom} \cong 27.6 + 42.9 + 13.4 \cong 84\,\mathrm{W}$$

10.3.5 Heat capacities

The energies to be stored in the lid, pan, and heater are considered to be identical to those of the dual-wall pan:

$$W_{lid} \cong 6.7 \text{ Wh}$$

$$W_{pan} \cong 4 \text{ Wh}$$

$$W_{heater} \cong 1.3 \text{ Wh}$$

$$W_{total} = W_{lid} + W_{pan} + W_{heater} \cong 6.7 + 4 + 1.3 \cong 12 \text{ Wh}$$

Evidently a rather large part of the energy is due to the lid: about 7 out of 12 Wh. This is caused by the relatively large specific heat of glass.

10.4 Conventional pan heat loss

Figure 2 (p. 11) is a simplified section view of a conventional pan sitting on a glass-ceramic cooking surface. Four heat flows are shown: $\dot{Q}_{top}$, $\dot{Q}_{side}$, $\dot{Q}_{glass}$, and $\dot{Q}_{bottom}$, that make up the total running heat loss from the heater-range-pan combination. See Hotplate, p. 11, for a description of the glass-ceramic panel and heating unit. Table 1, p. 19, shows the dimensions. The heat flows from top, side, and bottom are calculated.

10.4.1 Top

The top heat loss is taken to be equal to that of the simple pot (p. 50),

$$\dot{Q}_{top} = 27.6\,\mathrm{W}$$

10.4.2 Side

Also the side heat loss is taken to be equal to that of the simple pot (p. 51),

$$\dot{Q}_{side} = 42.9\,\mathrm{W}$$

10.4.3 Bottom

To get an idea of the heat flow $\dot{Q}_{bottom}$ through the insulator (Figure 2, p. 11) we make a rough estimate of the heater temperature T_{heater} = 200°C. The insulator is a horizontal circular disc and a vertical cylinder with the following dimensions: mean diameter of cylinder D, mean height of cylinder H, and insulation thickness δ. The heat thermal conductivity of the insulator is k, and the ambient temperature T_{amb}.

D = 145 mm = 0.145 m

H = 14 mm = 0.014 m

δ = 12 mm = 0.012 m

k = 0.022 W/(m·K) (Microtherm, Table 2, p. 20)

T_{amb} = 20°C

The area of heat transmission becomes

$$A = \frac{\pi}{4} D^2 + \pi DH \cong \frac{\pi}{4} 0.145^2 + \pi 0.145 \cdot 0.014 \cong 0.0229\,\mathrm{m}^2$$

and the heat flow

$$\dot{Q}_{bottom} = \frac{k\,A(T_{heater} - T_{amb})}{\delta} \cong \frac{0.022 \cdot 0.0229(200-20)}{0.012} \cong 7.6\,\mathrm{W}$$

10.4.4 Glass ceramic

We shall refrain from calculating the theoretical heat loss by horizontal conduction through the glass-ceramic panel, as it is rather complicated. Instead we base the calculation on the measured total running power consumption in conjunction with the above three heat flows (see Energy consumptions compared, p. 24).

10.4.5 Heat capacities

The energies required to heat the lid, pan, and hotplate from T_l = 20°C are calculated. The high temperatures T_h of lid and pan are assumed to be 95°C, those of the glass-ceramic panel and heater, 200°C. For dimensions see Table 1, p. 19, for material properties, Table 2, p. 20.

$$W_{lid} = \frac{mc(T_h - T_l)}{3600} \cong \frac{0.405 \times 800(95-20)}{3600} \cong 6.8\,\mathrm{Wh}$$

$$W_{pan} \cong \frac{0.69 \times 470(95-20)}{3600} \cong 6.8\,\mathrm{Wh}$$

$$W_{glass\_ceramic} \cong \frac{0.178 \times 800(200-20)}{3600} \cong 7.1\,\mathrm{Wh}$$

The heater is assumed to be made out of constantan; the energy stored in it turns out to be insignificant:

$$W_{heater} \cong \frac{0.022 \times 384(200-20)}{3600} \cong 0.4\,\mathrm{Wh}$$

The total stored energy becomes

$$W_{total} = W_{lid} + W_{pan} + W_{glass\_ceramic} + W_{heater} \cong 6.8 + 6.8 + 7.1 + 0.4 \cong 21.1\,\mathrm{Wh}$$

The purpose of this work is to investigate the energy losses in electric surface cooking and how to minimize them. The case of cooking with dry heat (frying) is only treated superficially, concentrating on cooking with moist heat (boiling, steaming). The theoretical losses are calculated for a conventional pan used with a conventional glass-ceramic range and for two types of electric pan, one thermally insulated and the other without insulation. The calculated losses compare fairly well with the actual, measured losses.

It is concluded that in order to minimize energy consumption the following three measures should be taken: (1) Integrate heating element in pan, (2) Isolate pan, (3) Provide an "intelligent" power control. A working prototype of a saucepan, dubbed the EffiCooker, is constructed according to these principles. To demonstrate the energy saving some common cooking tasks are performed with the EffiCooker as well as with ordinary equipment. In these examples energy savings range from 28% to 81%. Furthermore, the EffiCooker is very user friendly.

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